

SINGLE-SHAFT COMBINED-CYCLE POWER GENERATION SYSTEM

L.O. Tomlinson and S. McCullough
 GE Power Systems
 Schenectady, NY

ABSTRACT

Combined-cycle power plants have demonstrated high thermal efficiency, high reliability/availability and economic power generation for application in base load and cyclic duty utility service. The single-shaft combined-cycle power generation system; in which the gas turbine, steam turbine and generator (STAG™) are installed in a tandem arrangement on a single shaft; has emerged as a preferred configuration resulting from simplicity of controls and operation and demonstrated high reliability.

This paper describes the design features, experience and operating characteristics of the General Electric pre-engineered product line of single-shaft STAG combined-cycle systems for power generation applications.

INTRODUCTION

Heat recovery type steam and gas turbine combined-cycle systems are the economic choice for gas- or oil-fired power generation. Integration with environmentally clean gasification systems is extending their economic application to low cost solid fuel utilization. The features contributing to their outstanding generation economics are:

- High thermal efficiency
- Low installed cost
- Fuel flexibility – wide range of gas and liquid fuels
- Low operation and maintenance cost
- Operating flexibility – base, mid-range, daily start
- High reliability
- High availability
- Short installation time
- High efficiency in small capacity increments
- Minimum environmental impact – low stack gas emissions and heat rejection

Combined-cycle power generation equipment is manufactured by GE in two basic configurations, single-shaft and multi-shaft. The single-shaft combined cycle system consists of one gas turbine, one steam turbine, one generator and one heat recovery steam generator (HRSG), with the gas turbine and steam turbine coupled to a single generator in a tandem arrangement. Multi-shaft combined-cycle systems have one or more gas tur-

bine generators and HRSGs that supply steam through a common header to a separate single steam turbine generator unit. Both configurations perform their specific functions, but the single-shaft configuration excels in the base load and mid-range power generation applications.

The multi-shaft combined-cycle system configuration is most frequently applied in phased installations in which the gas turbines are installed and operated prior to the steam cycle installation and where it is desired to operate the gas turbines independent of the steam system. The multi-shaft configuration was applied most widely in the early history of heat recovery combined-cycles primarily because it was the least departure from the familiar conventional steam power plants. The single-shaft combined-cycle system has emerged as the preferred configuration for single phase applications in which the gas turbine and steam turbine installation and commercial operation are concurrent.

The first GE single-shaft combined-cycle generation units entered service in 1968. The early units demonstrated the excellent generation economics that could be achieved by these simple, efficient, reliable and compact systems. The single-shaft combined-cycle applications are increasing as a result of: the power generation industry acceptance of GE's demonstrated outstanding operating characteristics; the development of larger gas turbines making possible large single combined-cycle units; the application of efficient but complex steam cycles (multiple pressure, reheat and steam cooling of the gas turbine) that are simplified by a unitized system. Also, the single-shaft system complements the unitized plant configuration that is most advantageous for solid fuel fired integrated gasification combined-cycle (IGCC) generation systems. Table 1, which shows the experience of GE single-shaft heat recovery combined-cycle generation systems, illustrates the increasing application of this type of equipment.

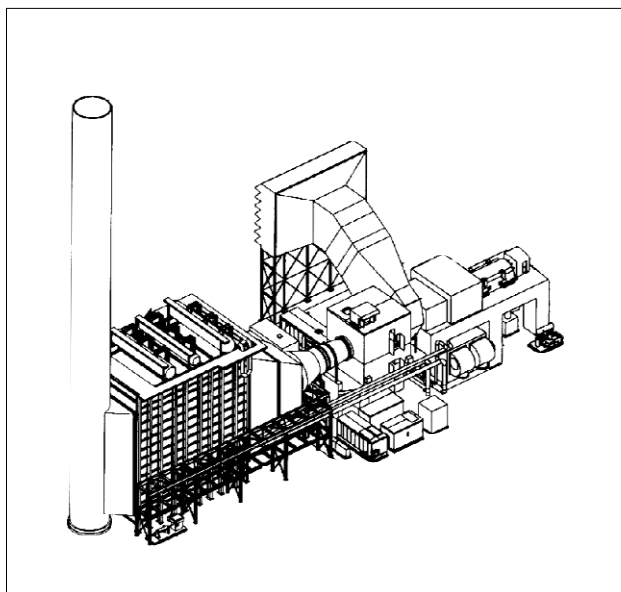
The H Technology combined cycles, Figure 1, are the most efficient power generation equipment available today. High efficiency is achieved by the high gas turbine firing temperature with minimum use of cycle air for cooling that is enabled by closed circuit steam cooling of the turbine. The single shaft configuration is ideally suit-

Table 1
SINGLE-SHAFT COMBINED-CYCLE EXPERIENCE

| Utility | Site | No. Units | Rating (MW) | | Gas Turbine | Commercial Operation | Operating Hours (Jan. 1996) |
|---------------------|-------------------------|-----------|-------------|---------------|-------------|----------------------|-----------------------------|
| | | | Unit | Plant | | | |
| Wolverine Electric | Michigan, USA | 1 | 21 | 21 | MS5001 | 1968 | 142,000 |
| City of Ottawa | Ottawa, KS, USA | 1 | 11 | 11 | MS3002 | 1969 | 115,000 |
| City of Clarksdale | Clarksdale, MS, USA | 1 | 21 | 21 | MS5001 | 1972 | 124,000 |
| City of Hutchinson | Hutchinson, MN, USA | 1 | 11 | 11 | MS3002 | 1972 | 84,000 |
| Salt River Projects | Santan, AZ, USA | 4 | 72 | 290 | MS7001B | 1974 | 220,000 |
| Arizona Public Ser. | Phoenix, AZ, USA | 3 | 83 | 250 | MS7001C | 1976 | 151,000 |
| Western Farmers | Anadarko, OK, USA | 3 | 93 | 278 | MS7001E | 1977 | 310,000 |
| Tokyo Electric | Futtsu, Japan | 14 | 165 | 2310 | MS9001E | 1986 | 657,100 |
| Chubu Electric | Yokkaichi, Japan | 5 | 112 | 560 | MS7001E | 1988 | 220,000* |
| Chugoku Electric | Yanai, Japan | 6 | 125 | 750 | MS7001E | 1990 | 56,000* |
| Ministry of Pet. | Lama Dien, China | 1 | 50 | 50 | MS6001B | 1990 | 44,000* |
| Kyushu Electric | Shin-Oita, Japan | 5 | 138 | 690 | MS7001EA | 1992 | 26,000* |
| National Power | Connah's Quay, UK | 4 | 350 | 1400 | MS9001F | 1995 | 16,000* |
| EPON | Netherlands | 5 | 350 | 1400 | MS9001FA | 1995 | 8,000 |
| 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 | 1995 | – |
| 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 | 1998 | – |
| Boffolora | Italy | 1 | 110 | 110 | MS6001FA | 1998 | – |
| Akzo | Delesto II, Netherlands | 1 | 360 | 360 | MS9001FA | 1998 | – |
| Total | | 85 | | 17,560 | | | 2,173,000 |

* Estimated

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Figure 1. H technology single-shaft combined-cycle

ed to this large, highly integrated combined cycle system.

STEAM CYCLE AND PERFORMANCE

A single-shaft STAG combined-cycle system has been optimized for each of the heavy duty gas turbines in the GE gas turbine product line. The performance ratings for the base configurations burning natural gas fuel are presented in Table 2. In the STAG system designation, the first digit designates a single gas turbine and the third digit with the following letters designates the gas turbine frame size.

The base configuration for the GE single-shaft product line is summarized in Table 3. The three pressure non-reheat steam cycle with natural circulation HRSG for the gas turbines with exhaust gas temperature of 1000 F/538 C is shown in Figure 2. The three-pressure reheat cycle that is applied with gas turbines with exhaust gas temper-

Table 2
SINGLE-SHAFT STAG PRODUCT LINE RATINGS

| UNIT DESIGNATION | STEAM CYCLE | NET PLANT POWER | NET PLANT HEAT RATE (LHV) | | THERMAL EFFICIENCY |
|------------------|------------------------|-----------------|---------------------------|--------|--------------------|
| | | | Btu/kWhr | KJkWhr | |
| 60Hz | | | | | |
| S106B | Non-Reheat, 3-Pressure | 59.8 | 7005 | 7390 | 48.7 |
| S106FA | Reheat, 3-Pressure | 107.1 | 6440 | 6795 | 53.0 |
| S107EA | Non-Reheat, 3-Pressure | 130.2 | 6800 | 7175 | 50.2 |
| S107FA | Reheat, 3-Pressure | 258.8 | 6090 | 6425 | 56.1 |
| S107G | Reheat, 3-Pressure | 350.0 | 5885 | 6210 | 58.0 |
| S107H | Reheat, 3-Pressure | 400.0 | 5690 | 6000 | 60.0 |
| 50Hz | | | | | |
| S106B | Non-Reheat, 3-Pressure | 59.8 | 7005 | 7390 | 48.7 |
| S106FA | Reheat, 3-Pressure | 107.4 | 6420 | 6775 | 53.2 |
| S109E | Non-Reheat, 3-Pressure | 189.2 | 6570 | 6935 | 52.0 |
| S109EC | Reheat, 3-Pressure | 259.3 | 6315 | 6660 | 54.0 |
| S109FA | Reheat, 3-Pressure | 376.2 | 6060 | 6395 | 56.3 |
| S109H | Reheat, 3-Pressure | 480.0 | 5690 | 6000 | 60.0 |

Notes: 1. Site Conditions-59 F, 14.7 psia, 60% RH (15 C, 1.013 bar, 60%)

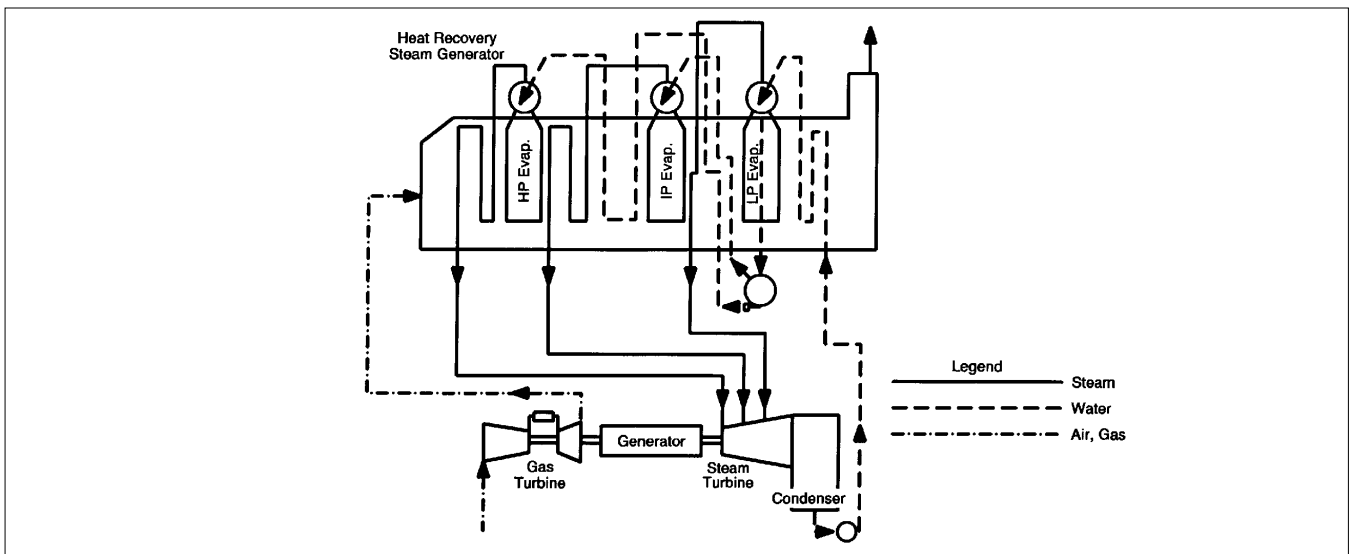
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Table 3
SINGLE-SHAFT STAG COMBINED-CYCLE BASE CONFIGURATION

- 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 1000°F (538°C)
 - Feedwater Heating by Exhaust Gas
 - Feedwater Deaeration in Condenser
 - Natural or Forced Circulation HRSG Evaporators
- Gas Turbine With Dry Low NO_x Combustors
- Once-Through Condenser Cooling Water System
- Integrated Equipment and Control System

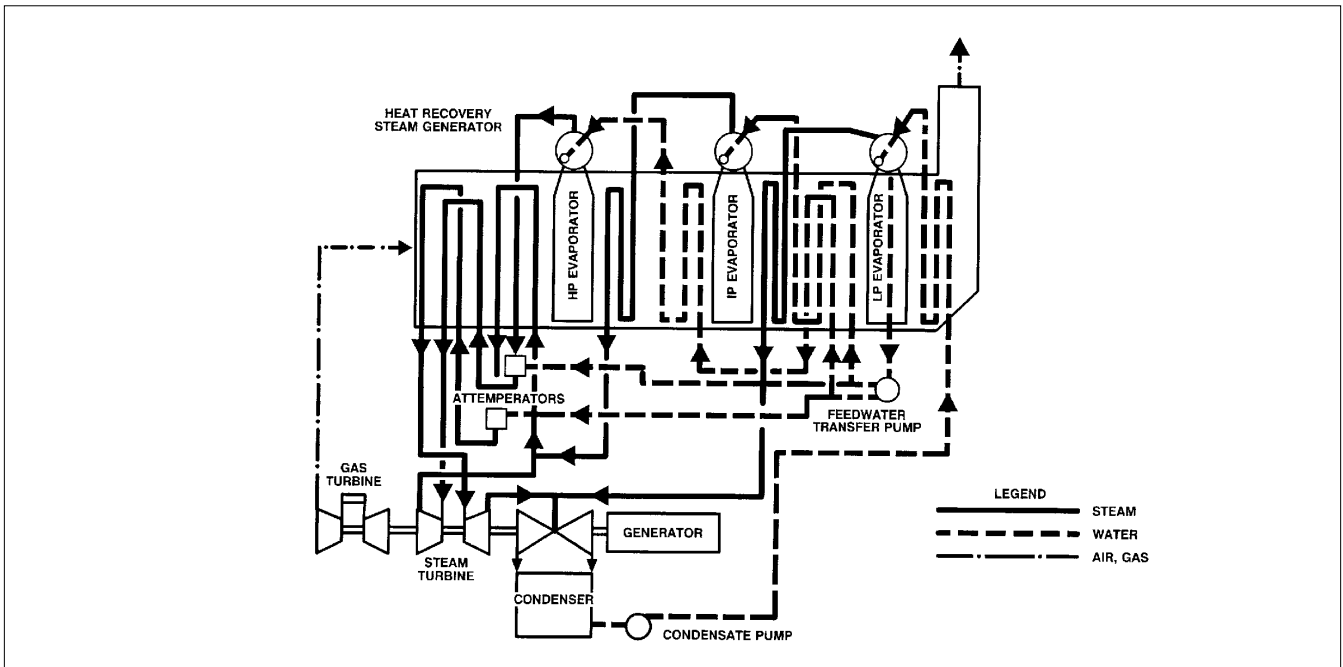
ature higher than 1000 F/538 C is shown in Figure 3. Figure 4 shows the three pressure reheat steam cycle that is integrated with the steam cooling system for the H technology gas turbine. The nominal steam conditions at rated output are presented in Table 4 and the major equipment for the single-shaft product line is presented in Table 5.

The single-shaft combined-cycle units follow the typical ambient temperature effects for GE STAG combined-cycle generation systems as shown in Figure 5. The heat rate does not vary significantly with ambient air temperature but the power output increases significantly at low ambi-



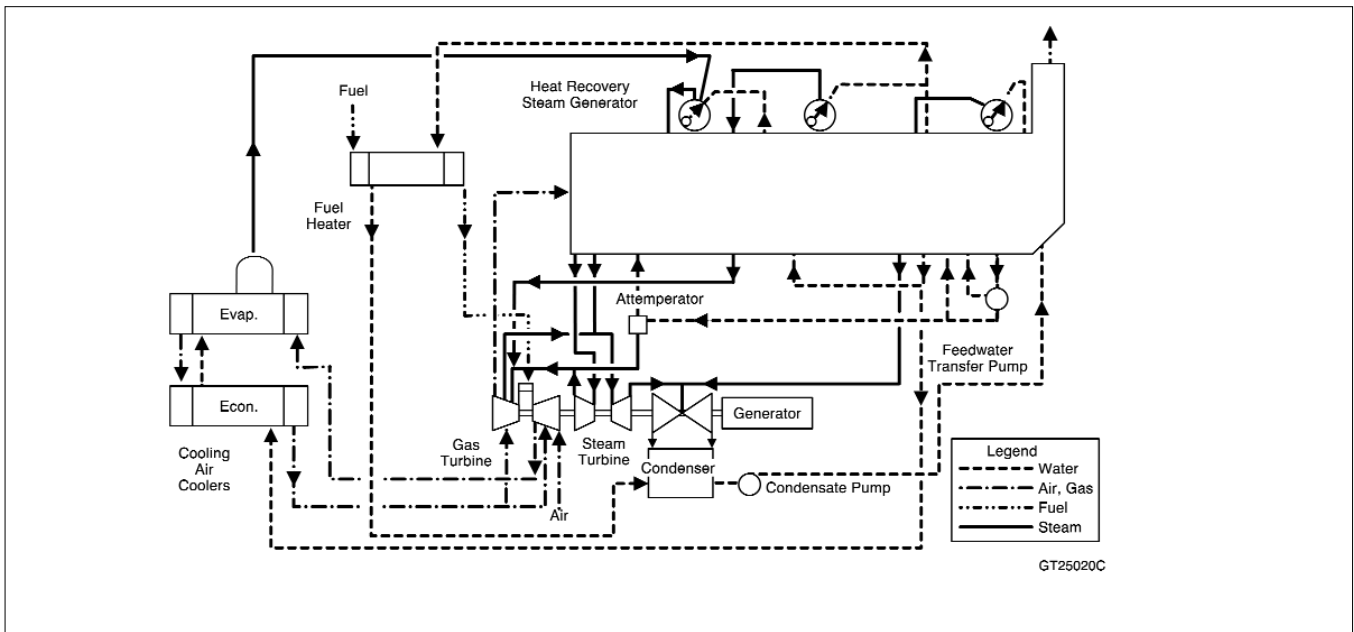
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Figure 2. Single-shaft, combined-cycle, three-pressure non-reheat steam cycle



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Figure 3. Single-shaft, combined-cycle, three-pressure reheat steam cycle



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GT25020C

Figure 4. STAG 107H/109H cycle diagram

Table 4
PRODUCT LINE NOMINAL STEAM CONDITIONS

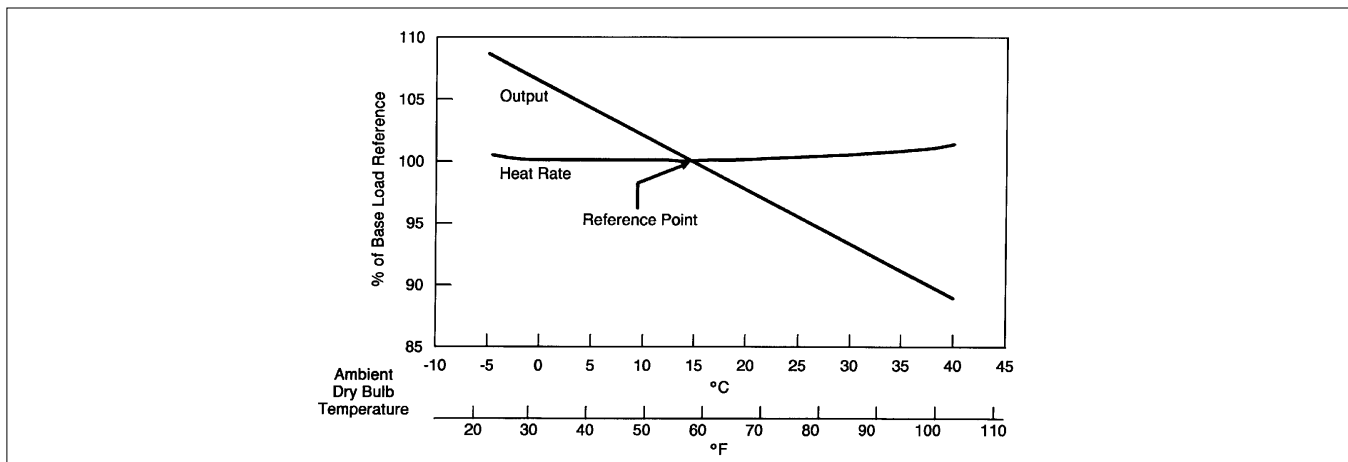
| Heat Recover Feedwater Heating Steam Cycle | Non-Reheat Three-Pressure | | | Reheat Three-Pressure | |
|--|------------------------------|-------------|-------------|--------------------------|---------------|
| | ≤ 40 | < 40 | > 60 | 61 | > 100 |
| Steam Turbine Size (MW) | 820 | 960 | 1200 | 1400 | 1800 |
| Throttle Pressure psig (bar) | (56.4) | (66.1) | (82.6) | (96.4) | (124) |
| Throttle Temp. Approach °F to Exhaust Gas Temp. (°C) | 45 (25) | 45 (25) | 45 (25) | 70 (39) | 1050 (28) |
| Reheat Pressure psig (bar) | - | - | - | 300-400 (20.6-27.5) | 450 (31.0) |
| Reheat Temperature °F (°C) | - | - | - | 1000 (538) | 1050 554 |
| I.P. Admission Pressure psig (bar) | 100 (7) | 120 (8) | 155 (11) | 300-400 (20.6-27.5) | 450 (31.0) |
| I.P. Temp-Approach to Gas °F Temp. Upstream of SPHTR. (°C) | 20 (11) | 20 (11) | 20 (11) | 20 (11) | 20 (11) |
| L.P. Admission Pressure psig (bar) | 25 (1.7) | 25 (1.7) | 25 (1.7) | 40 (2.8) | 40 (2.8) |
| L.P. Temp. Approach to Gas °F Temp. Upstream of SPHTR. (°C) | 20 (11) | 20 (11) | 20 (11) | 20 (11) | 20 (11) |

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Table 5
SINGLE-SHAFT STAG PRODUCT LINE EQUIPMENT

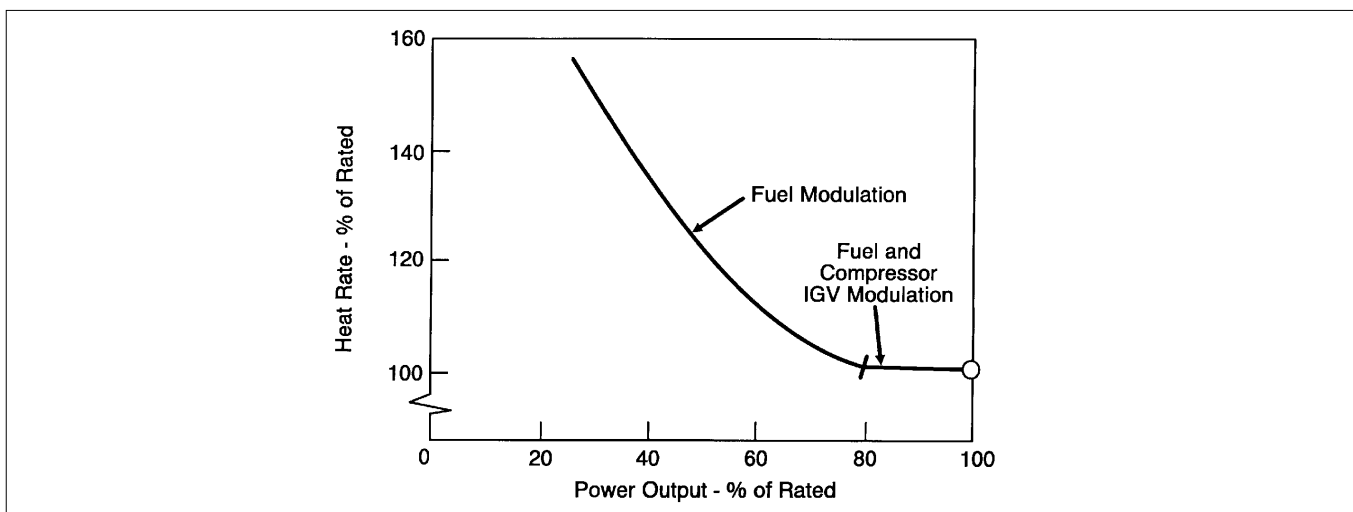
| STAG Designation | Gas Turbine | HRSG Type | Steam Turbine | | | |
|------------------|-------------|---------------------|---------------|------|---------|---------------|
| | | | LSB Length | | Exhaust | |
| | | | IN | MM | NO | Configuration |
| 60 Hz | | | | | | |
| S106B | PG6541B | Non-Reheat, Unfired | 23 | 585 | 1 | Axial |
| S106FA | PG6101FA | Reheat, Unfired | 30 | 762 | 1 | Axial |
| S107EA | PG7111EA | Non-Reheat, Unfired | 30 | 762 | 1 | Axial |
| S107FA | PG7231FA | Reheat, Unfired | 30 | 762 | 2 | Down |
| S107H | MS7001H | Reheat, Unfired | 40 | 1016 | 2 | Down |
| 50 Hz | | | | | | |
| S106B | PG6541B | Non-Reheat, Unfired | 23 | 585 | 1 | Axial |
| S106FA | PG6101FA | Reheat, Unfired | 26 | 660 | 1 | Axial |
| S109E | PG9171E | Non-Reheat, Unfired | 33.5 | 851 | 1 | Down |
| S109EC | PG9231EC | Reheat, Unfired | 33.5 | 851 | 2 | Down |
| S109FA | PG9311FA | Reheat, Unfired | 33.5 | 851 | 2 | Down |
| S109H | MS9001H | Reheat, Unfired | 42 | 1067 | 2 | Down |

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Figure 5. Ambient temperature effect on performance



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Figure 6. Typical single-shaft combined-cycle unit heat rate variation with power output

ent air temperature. Figure 6 illustrates typical part load performance for a single-shaft combined-cycle unit. The heat rate is near the rated value from approximately 80% to 100% load, while the gas turbine inlet guide vanes are modulated to maintain high cycle temperature. At lower load, the output is varied by variation in fuel flow with varying cycle temperature so the heat rate increases as load is reduced.

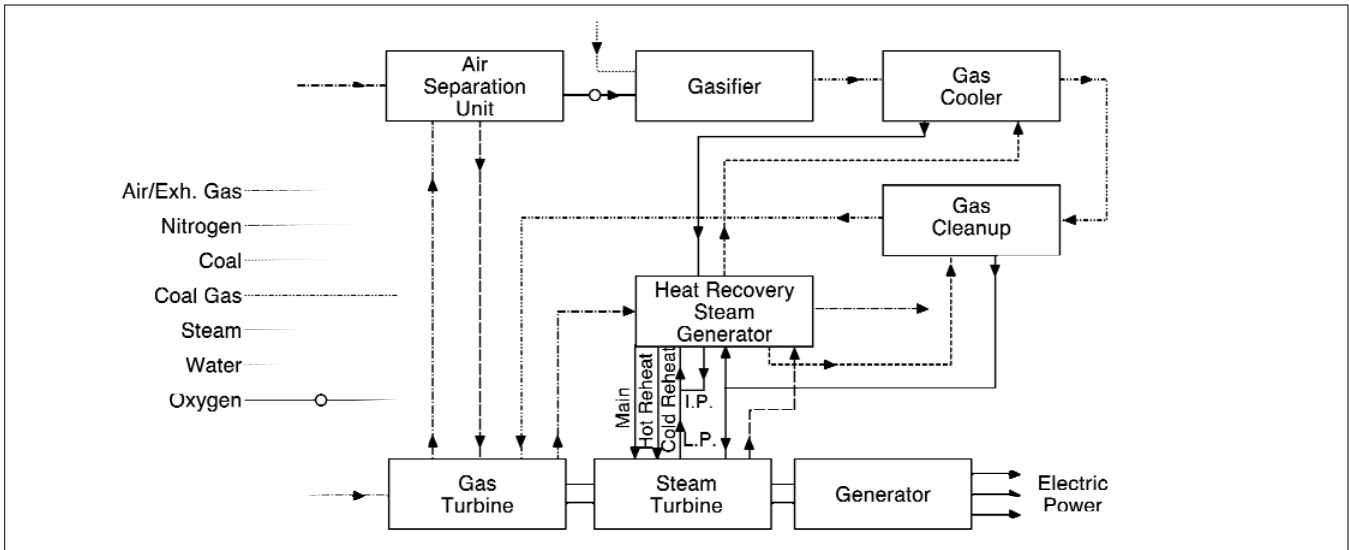
ENVIRONMENTAL IMPACT

Minimum environmental impact is a hallmark of all combined-cycle systems. Exhaust emissions are low as a result of high quality combustion in the gas turbines, and heat rejected to cooling water is low since the power produced by the steam cycle is one-third of the unit power output. The Dry Low NO_x combustion systems achieve NO_x emissions of 25 ppmvd at 15% oxygen

(43 g/GJ) or less. Water or steam injection abates NO_x emissions to 25 ppmvd at 15% oxygen (43 g/GJ) when burning distillate oil fuel. IGCC systems can achieve NO_x emissions as low as 9 ppmvd at 15% oxygen (16 g/GJ) with nitrogen injection or fuel moisturization by saturation.

For environmentally sensitive applications where extremely low NO_x emissions are required, selective catalytic reduction (SCR) can be readily adapted to single-shaft combined-cycle systems. SCRs require a gas temperature range lower than the gas turbine exhaust gas temperature so they are installed in the HRSG in the appropriate zone to suit their operating temperature range. The single-shaft combined-cycle does not have an exhaust gas bypass stack, so the exhaust gas passes through the SCR for reducing NO_x emissions at all times.

The single-shaft combined-cycle is also ideally suited for incorporation into IGCC systems which can burn coal in an environmentally acceptable



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Figure 7. Unitized IGCC system

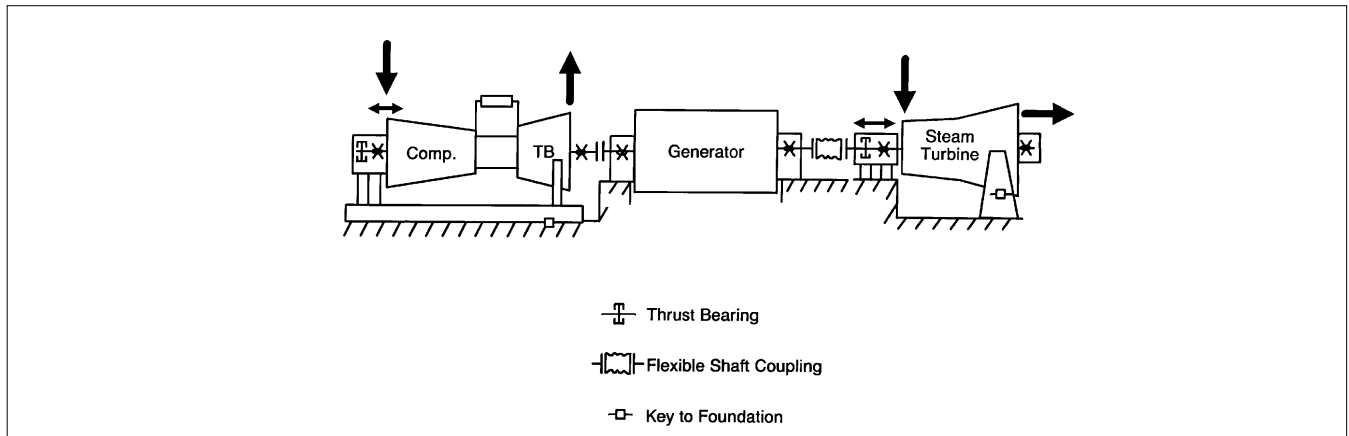
manner. The unitized system enables convenient integration with a gasifier to form a flexible operating unit. Unitizing the IGCC system is highly desirable because there are a large number of flow interconnections between components. The unit system does not require the control complexity to split flows between components as would be required for non-unitized systems. Figure 7 presents a unitized IGCC system with air, coal gas, nitrogen, water and steam interchange between components.

EQUIPMENT CONFIGURATIONS

The single-shaft combined-cycle units with non-reheat steam turbine capability less than approximately 40 MW for 60 Hz units and 60 MW for 50 Hz units are configured with the generator between the gas turbine and the steam turbine, as

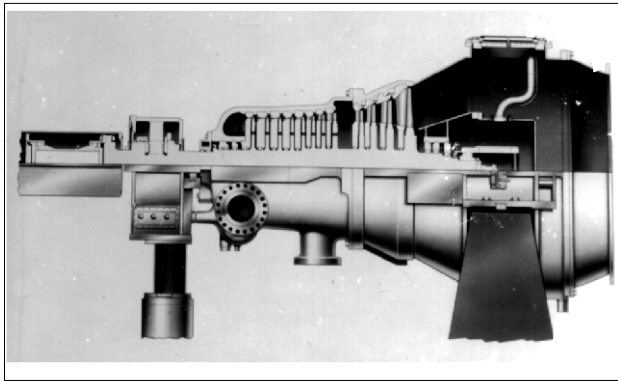
shown in Figure 8. This configuration is applied for the STAG 107EA and STAG 109E systems. This enables the equipment to be installed on a slab type foundation. The gas turbine and steam turbine both have thrust bearings for individually controlling their shaft position. A flexible coupling between the steam turbine and generator accommodates the relative movement of the rotor between the generator and the steam turbine.

A cross section of the steam turbine applied in a typical STAG 107EA system is shown in Figure 9. This is a simple, single casing unit with full arc steam admission and off-chest stop/control valves. This steam turbine with axial exhaust drives from the inlet end through a diaphragm type flexible coupling. All connections are flanged since the steam turbine is moved to remove the generator rotor. A similar steam turbine configuration is applied on the STAG 109E, STAG 106FA and STAG 106B single-shaft units.



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Figure 8. STAG 107EA, 109E configuration

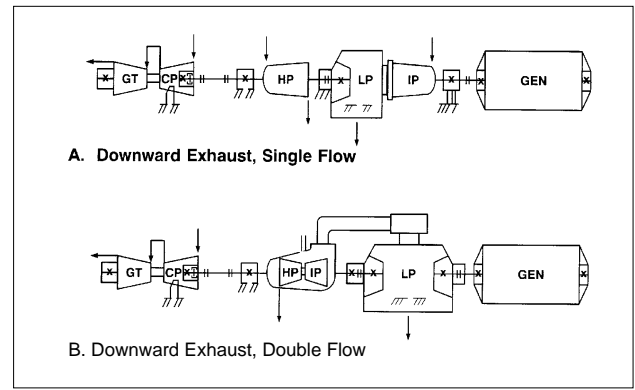


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Figure 9. STAG 107EA steam turbine

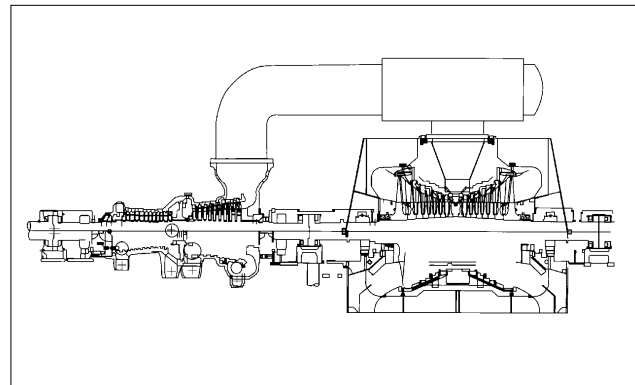
Single-shaft combined-cycle units with larger, reheat steam turbines are configured with the steam turbine between the gas turbine and the generator as shown in Figure 10. The steam turbine is not required to drive through the generator collector and the more complex steam turbine is not required to be moved for generator rotor removal. A single thrust bearing in the gas turbine controls the rotor position. Solid couplings are used throughout the equipment train.

The reheat steam turbine with double flow exhaust for application on the STAG 107FA with low exhaust pressure and the 50 Hz STAG 109FA combined-cycle is shown in Figure 11. The opposed flow HP-IP section is keyed at the front standard which is near the unit thrust bearing in the gas turbine. Tie rods from the front standard also fix the position of the gas turbine thrust bearing in relation to the steam turbine. Figure 12 shows a cross-section of the MS7001FA gas turbine and single flow steam turbine in a STAG 107FA



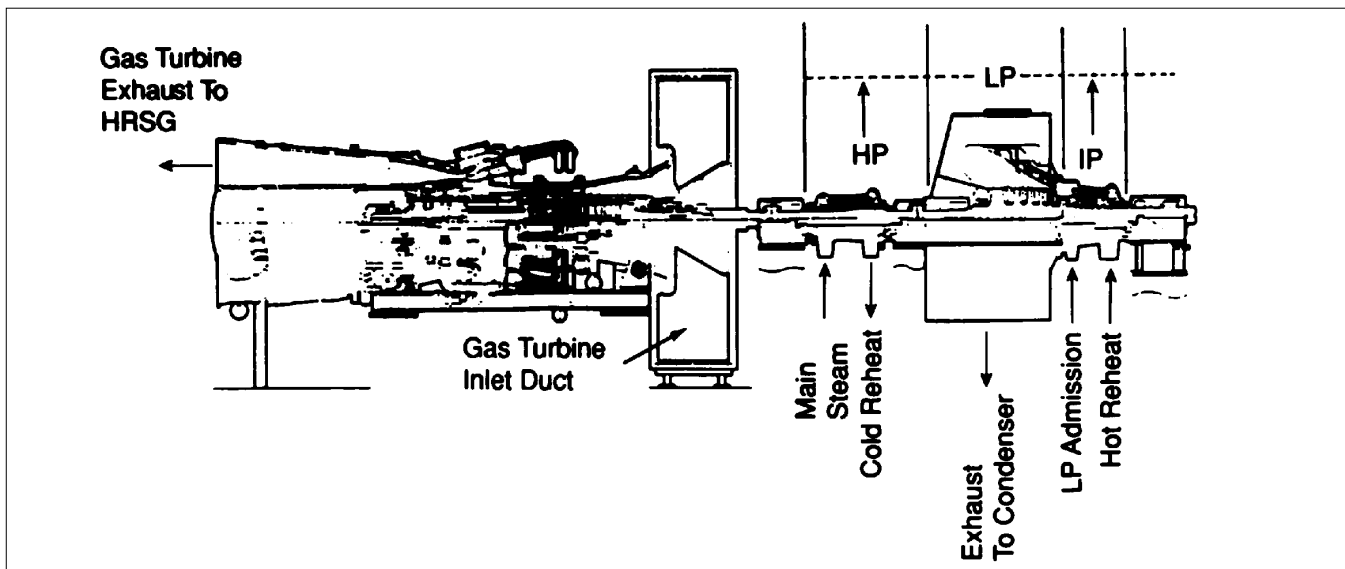
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Figure 10. Large single-shaft combined-cycle equipment configuration



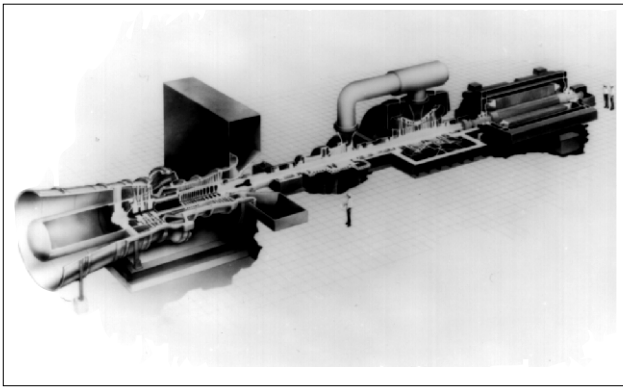
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Figure 11. Two-flow reheat steam turbine



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Figure 12. STAG 107FA combined-cycle unit with single-flow steam turbine and gas turbine



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Figure 13. STAG 109FA perspective view

combined-cycle unit. Figure 13 shows a perspective view of the rotating equipment for a STAG 109FA combined-cycle unit.

The simplicity of the GE single shaft combined cycle equipment provides easy starting and operation and minimum maintenance which results in high reliability and availability. A clutch in the shaft line to enable independent operation of the gas turbine and generator is not included because it requires either an HRSG gas bypass or large steam by pass to a dump condenser or to the main steam turbine exhaust condenser to enable gas turbine operation. These either complicate the combined cycle system or they prevent performance of maintenance work on the steam turbine during independent operation of the gas turbine.

A comprehensive study of equipment configurations was conducted during the development of the H technology single shaft combined-cycles. The configuration with the generator between the gas turbine and steam turbine with a clutch between the steam turbine and generator was included in this study. While this configuration enables a low, slab type foundation for applications with single flow, axial exhaust steam turbines, the installed cost advantage achieved by lower foundation pedestal cost is offset by other costs resulting from the increased train length and the requirement for special features to enable removal of the generator rotor for inspection and maintenance. A summary of the comprehensive installed cost analysis is presented on Table 6. Since there is not a distinct cost or operational advantage, the GE large single shaft combined-cycles will continue to be configured with the gas turbine exhausting axially to the HRSG and driving through the steam turbine to the generator because of the following:

Compactness - less land space - higher power density

Simplicity - no clutch and auxiliaries, no gas bypass damper, no dump condenser, etc.

Maintainability - easy access for convenient maintenance

Operability - Simplest equipment and control configurations

AUXILIARIES

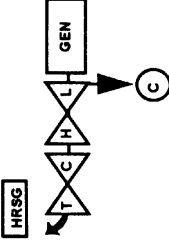
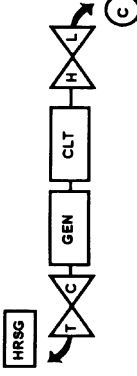
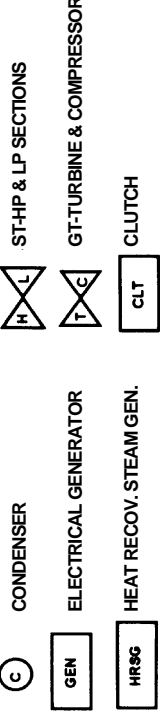
The unit mechanical auxiliaries include the condenser and auxiliaries, circulation water pumps, condensate pump, feedwater pump, condenser cooling water pump and HRSG evaporator circulation pumps, if required. Deaeration of feedwater in the condenser has been applied on most GE single-shaft combined-cycle units. Alternately, positive pressure deaeration by a deaerator integral with the low-pressure evaporator in the HRSG or a separate deaerator with steam supplied from the low-pressure evaporator can be applied. Single train mechanical auxiliaries have been applied on all single-shaft units. The system simplicity resulting from application of single train auxiliaries has contributed to the outstanding reliability and availability achieved by these systems.

Common lubrication system and hydraulic power systems are employed for the major equipment train. These are critical systems and are equipped with redundant pumps, including a d-c powered lubrication pump for emergency shutdown and cooldown in event of a failure of the a-c auxiliary power supply. The unit accessories for the STAG 106FA, 107FA and 109FA are motor driven. These accessories are packaged on an integrated skid installed beside the unit in the basement. The unit accessories for the STAG 106B, 107EA, STAG 109E and 109EC are shaft driven from an accessory gear unit mounted on the lubricating oil reservoir which is located at the compressor end of the gas turbine.

Two methods of starting the large STAG 107FA, STAG 109EC and STAG 109FA combined-cycle units are available. These are the steam turbine with steam supplied from an auxiliary steam supply or boiler, or the generator may be used with power furnished from the auxiliary electrical system through a variable frequency load commutated inverter (LCI) system. The smaller STAG 106B, STAG 106FA, STAG 107EA and STAG 109E single-shaft units are started with an electric motor and torque convertor.

A small auxiliary steam supply is required for the steam turbine seals for starting. The auxiliary steam requirement varies from approximately 2000 lb/hr/907 kg/hr for the STAG 106B unit to 4000 lb/hr/1814 kg/hr for the STAG 109FA unit. Auxiliary steam conditions are 600 F/316 C and 100 psig/6.9 atg. An auxiliary steam header with

Table 6
ALTERNATE SINGLE-SHAFT POWER PLANT DESIGN INSTALLED COST EVALUATION

| <p>PLANT COST COMPARISON SINGLE-SHAFT COMBINED-CYCLE ALTERNATE POWER PLANT ANALYSIS STAG 10TH OR 109H</p> | <p>PROVEN GE POWER TRAIN</p>  | <p>ALTERNATE POWER TRAIN EVALUATION EXAMPLE</p>  | <p>SYMBOL LEGEND AND EVALUATION NOTES ON ALTERNATE POWER PLANT DESIGN</p>  |
|---|--|--|---|
| TURBINE-GENERATOR-CONDENSER LENGTH | BASE LENGTH / COST | INCREASE - 12M (39 FT) | CLUTCH, COUPLING AND AXIAL-FLOW CONDENSER WIDTH ADDED TO MAIN POWER TRAIN (MPT) LENGTH |
| TURBINE-GENERATOR BUILDING AREA COST | BASE AREA / COST | INCREASE - 420M ² (4,500 SQ. FT) | AXIAL-FLOW CONDENSER ADDED TO MPT LENGTH, PLUS EXTRA LENGTH OF CLUTCH ASSEMBLY |
| ST-G SHAFT CENTERLINE ELEVATION COST | BASE ELEVATION / COST | DECREASE - 3M (10 FT) | STEAM PPG AND VALVES MOVED UP TO OPERATING FLOOR |
| GAS TURBINE COST | BASE COST | INCREASE | SECOND TURNING GEAR REQUIRED |
| STEAM TURBINE COST | BASE COST | COMPARABLE / INCREASE | AXIAL-FLOW VS. DOWN FLOW EXHAUST DESIGN; ADDITIONAL THRUST BRG. |
| GENERATOR COST | BASE COST | INCREASE | DOUBLE-END DRIVE ROTOR DESIGN COST |
| T-G AUXILIARIES COST | BASE COST | INCREASE | INCREASED - OIL CONSUMPTION OF CLUTCH AND THRUST BEARING, INCREASED COMPLEXITY OF REHEAT VALVE AND OVER SPEED PROTECTION |
| HRSG COST | BASE COST | DECREASE | LOWER SUPPORT ELEVATION |
| CONDENSER COST | BASE COST | INCREASE | TYPICAL AXIAL-FLOW CONDENSER, SIMPLE-CYCLE OPERATION "DUMPING" |
| STATIC START COST | BASE COST | DECREASE | DECREASED STARTING POWER - GT AND GENERATOR ONLY |
| ADDITIONAL MAIN POWER TRAIN (MPT) EQUIP. | BASE COST | INCREASE | CLUTCH, COUPLING, LUBRICATION ELECTRIC POWER AND ENCLOSURE |
| PEDESTAL / FOUNDATION COST | BASE COST | INCREASE / DECREASE | INCREASED LENGTH OF SUPPORT SLABS / SHORTER COLUMNS |
| BUILDING / STRUCTURE COST | BASE COST | INCREASE / DECREASE | INCREASE AREA DUE TO INCREASED MPT LENGTH; MAINT. CRANE SIZED TO LIFT ASSEMBLED GENERATOR? / DECREASED VOLUME DUE TO LOWER BLDG. ELEV |
| ACOUSTIC TREATMENT COST | BASE COST | INCREASE | POSSIBLE ADDITIONAL ENCLOSURE FOR CLUTCH EQUIPMENT |
| STEAM LINES, VALVES, SUPPORTS, INSULATION COST | BASE LENGTH / COST | INCREASE | LONGER PPG RUNS FROM HRSG TO STEAM TURBINE |
| AUXILIARIES PPG INTERCONNECTIONS COST | BASE LENGTH / COST | DECREASE / INCREASE | LOWER ELEVATION / LONGER DISTANCE BETWEEN MAJOR LOADS, e.g. THRUST BEARINGS |
| AUXILIARY BOILER COST | BASE COST | DECREASE / INCREASE | HRSG USED FOR SEALING AND COOLING STEAM / ADDITION OF SUPERHEATER AT TEMPERATURE |
| HIGH VOLTAGE CIRCUITS COST | BASE COST | INCREASE | LONGER OUTPUT POWER AND START-UP TRANSFORMER CIRCUITS RUN NORMAL TO T-G AXIS |
| MEDIUM / LOW VOLTAGE CIRCUITS COST | BASE COST | DECREASE | LOWER ELEVATION, SOME SHORTER CIRCUITS |
| EFFICIENCY | BASE EFFICIENCY | COMPARABLE | POSSIBLE DECREASED BACK PRESSURE FOR AXIAL EXHAUST |
| OPERATIONAL COST | BASE COST | COMPARABLE | FASTER START-UPS, I.E. FIRST GT-G FOLLOWED BY ST (NON "H" TECHNOLOGY) |
| MAINTENANCE COST | BASE COST | INCREASE | DIFFICULT GENERATOR ROTOR REMOVAL; ADD'L CLUTCH MAINTENANCE; INDEPENDENT GT & ST MAINT. |
| CONSTRUCTION COST / SCHEDULE | BASE COST / SCHEDULE | DECREASE / INCREASE | FLEXIBLE CONDENSER & ST INSTALLATION SCHEDULE ADDITIONAL MPT EQUIPMENT TO INSTALL, ALIGN, TEST, ETC. |



GT15302

Figure 14. STAG 109E equipment



GT 08617-1F

Figure 16. Western Farmers Electrical Cooperative Plant



GT16590

Figure 15. 2310 MW TEPCO Futtsu station – 14 STAG units

steam supplied from an operating unit is typically applied on installations with multiple units.

Exhaust gas bypass stacks and dampers are not required on single-shaft combined-cycle units. A simple steam bypass from the superheaters direct to the condenser is applied on units either with reheat or non-reheat steam systems.

PLANT ARRANGEMENTS

The single-shaft STAG combined-cycle equipment is configured for low cost installation with convenient maintenance. The STAG 106B, 107EA and 109E units are arranged for installation on a slab-type foundation with minimum basement. The modern, high technology units with multiple pressure, reheat cycles are typically installed on a pedestal to allow space for the piping. Those systems with the steam turbine between the gas turbine and generator are usually arranged with the steam turbine exhaust condenser below the steam turbine requiring a pedestal type foundation.

The STAG 109E rotating equipment, shown in Figure 14 during erection at the TEPCO Futtsu Station, is designed for inexpensive installation on a

slab-type foundation. While it is not required, this turbine building has a basement for convenient accommodation of the condenser, the auxiliaries, and steam and water piping. An aerial view of the 2310 MW TEPCO Futtsu Station is shown in Figure 15. Seven units are installed in each of the two turbine buildings. Figure 16 shows the Western Farmers Electric Cooperative Anadarko plant which has three STAG 107E units. These units are installed on slab type foundations with piping installed above the floor and convenient maintenance access and laydown space provided by an open aisle between the units.

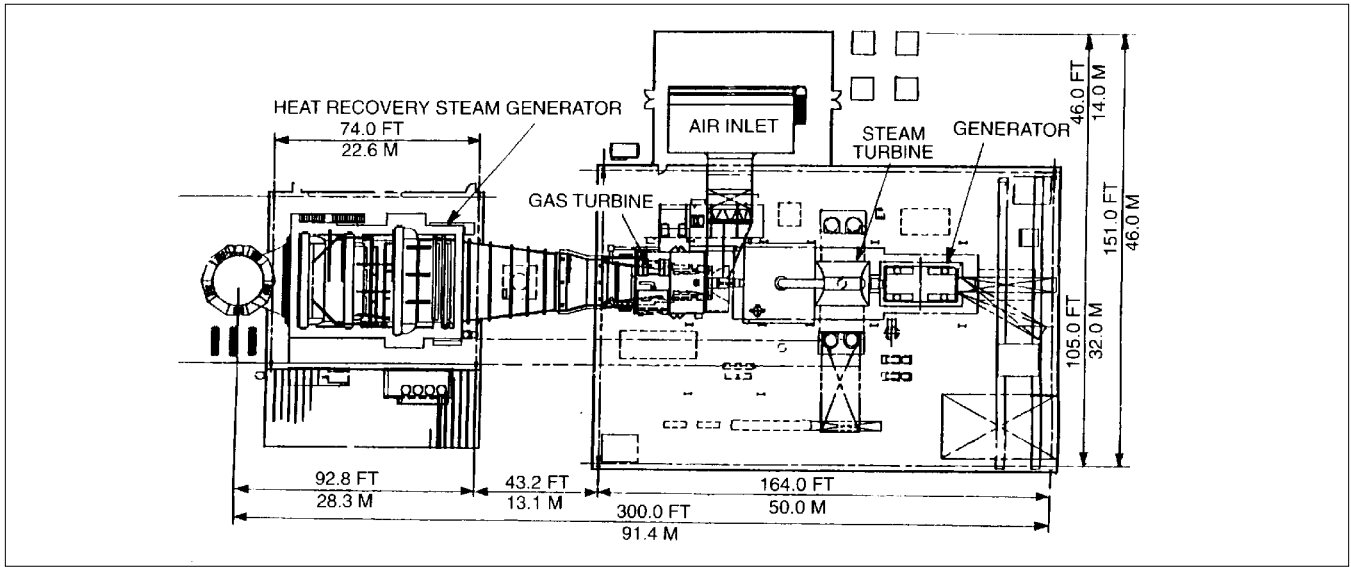
A typical plant arrangement for the STAG 107FA single-shaft combined-cycle is shown in Figures 17, 18 and 19 for an indoor installation. The turbine building includes a basement for the condenser, auxiliaries and piping. This arrangement includes HRSGs with horizontal gas flow and natural circulation evaporators.

The Tokyo Electric Power Co. STAG 109FA installation at the Yokohama Station has been designed with the air intake duct routed through the foundation under the gas turbine. This arrangement minimizes building plan space. A rendering of this 2800 MW plant with eight STAG 109FA units is shown in Figure 20.

CONTROLS AND OPERATION

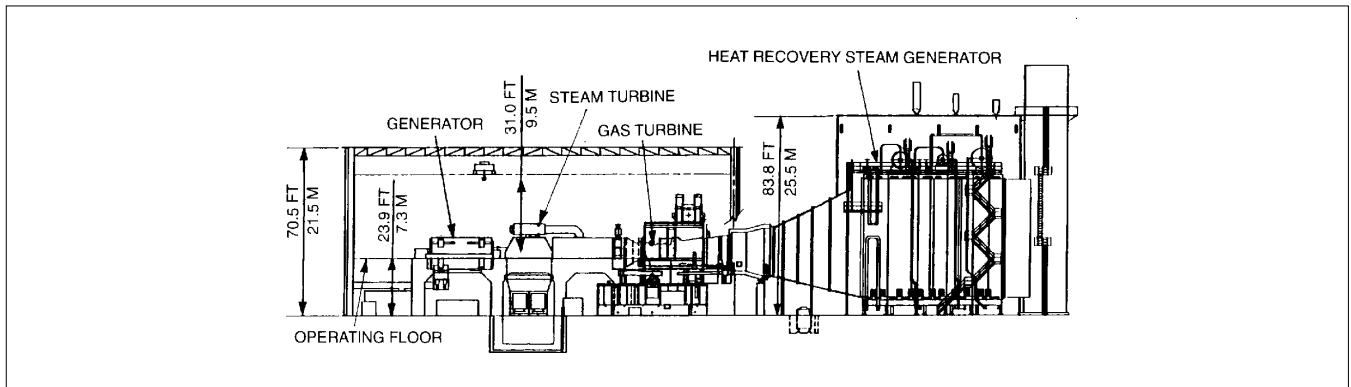
Simplicity of controls and operating flexibility are key features of single-shaft combined-cycle systems. Easy starting and excellent load following capability suit these systems for daily start, mid-range peaking service, and their high reliability and availability suits them for base load, continuous operation.

Each single-shaft unit operates independently, so a problem on one unit does not affect others. Differentiating from the multi-shaft combined-cycles, where the steam turbine generator has different operating characteristics than the gas tur-



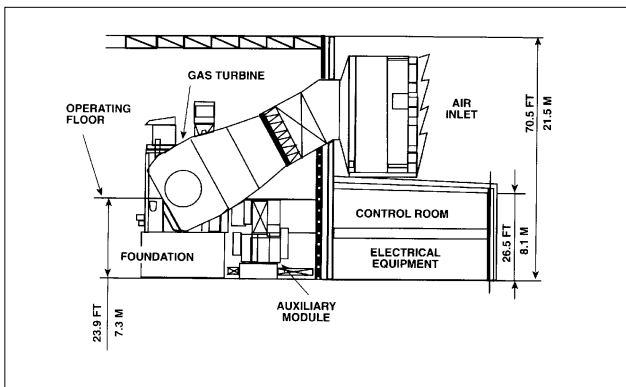
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Figure 17. STAG 107FA equipment arrangement plan



GT23836

Figure 18. STAG 107FA equipment arrangement elevation



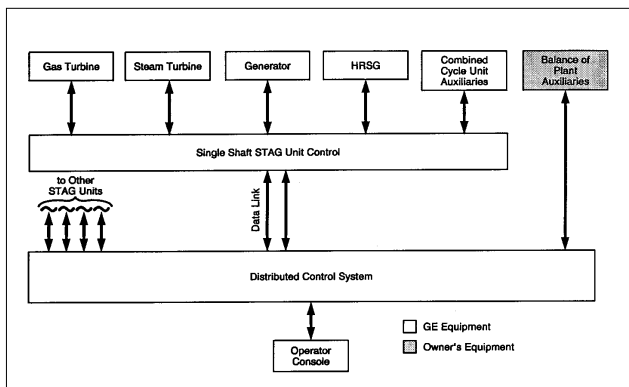
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Figure 19. STAG 107FA elevation section through gas turbine



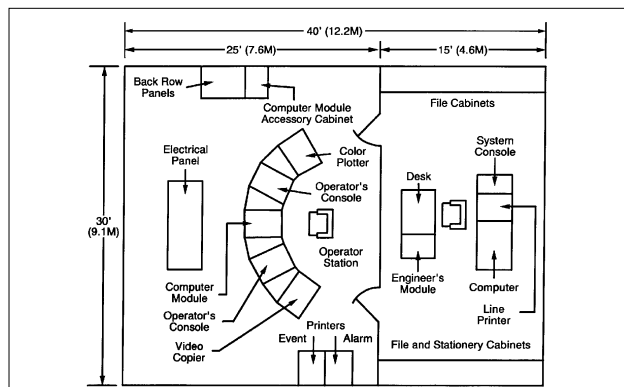
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Figure 20. 2800-MW TEPCO Yokohama Station



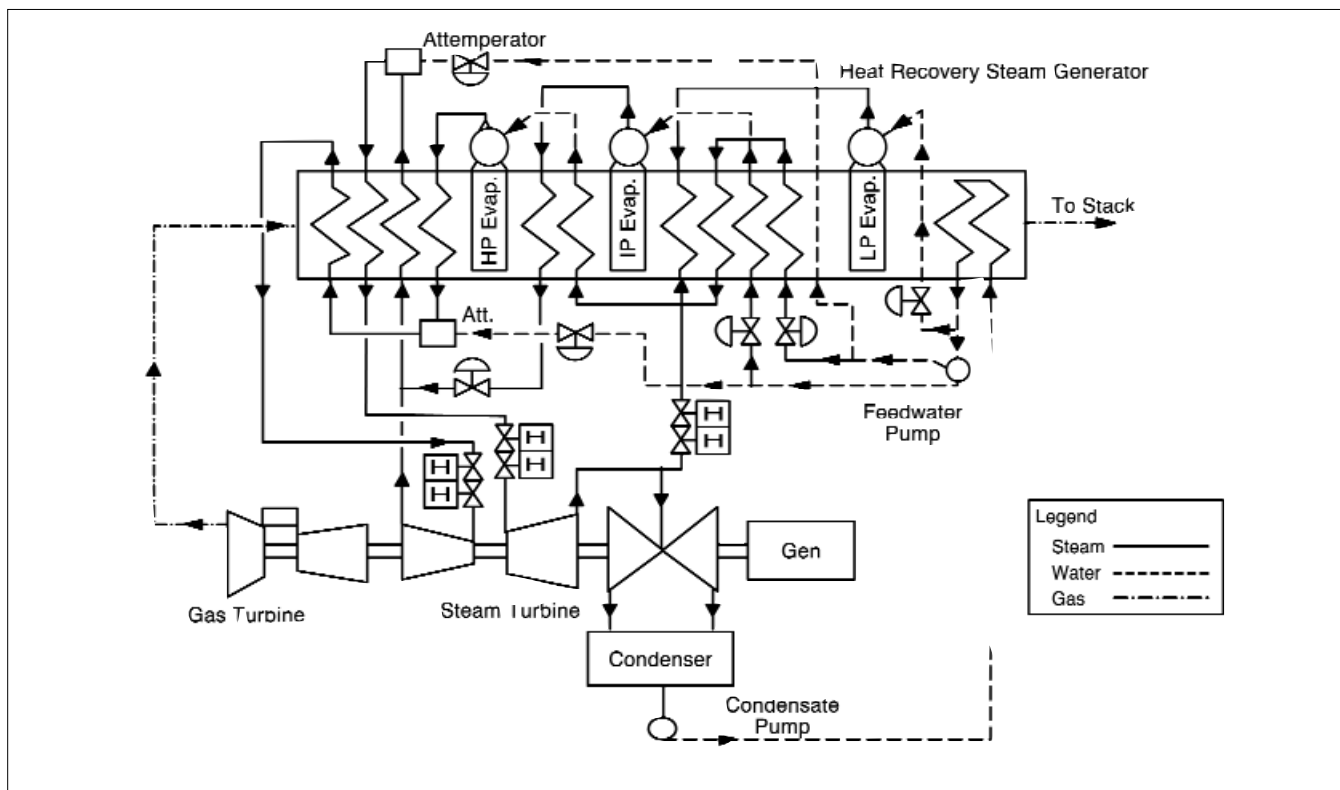
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Figure 21. Control configuration



GT16980A

Figure 22. Typical control room layout



GT23838A

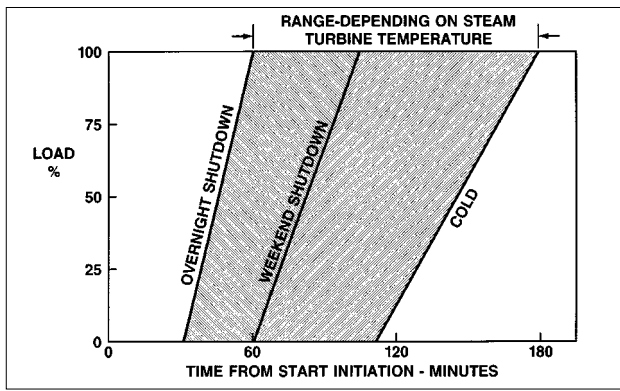
Figure 23. Reheat single-shaft combined-cycle diagram

bine generator, multiple single-shaft units in a station have identical operating requirements.

A block diagram of a typical distributed control system for a plant with multiple single-shaft units is shown in Figure 21. A unit control system, which is usually installed near the major equipment, controls and protects the single-shaft unit. The unit control system communicates with the central plant control through a data link. The central control is usually in a remote central control room. Figure 22 shows a typical central control room layout. This system enables one central room operator to coordinate the operation of several single-shaft combined-cycle units.

Complex steam systems such as the three-pressure reheat system are simplified in the single-shaft combined cycle. The diagram of the steam cycle in Figure 23 illustrates some key areas of simplification. Valves which isolate high pressure steam lines, reheaters and low pressure steam lines are not required as they are for multi-shaft reheat combined cycles.

When the steam turbine shell and rotor are hot, the starting and loading are fast, typically one hour following a 12-hour overnight shutdown. The starting and loading time after a weekend shutdown is approximately two hours, and three hours if the steam turbine is cold as shown in Figure 24. Figure



GT19972

Figure 24. Starting and loading characteristics

25 shows the variation of several key parameters during a normal shutdown and hot start for a STAG 109E unit at the TEPCO Futtsu Station. This unit completes a hot start within a one hour period following an overnight shutdown period.

RELIABILITY AND AVAILABILITY

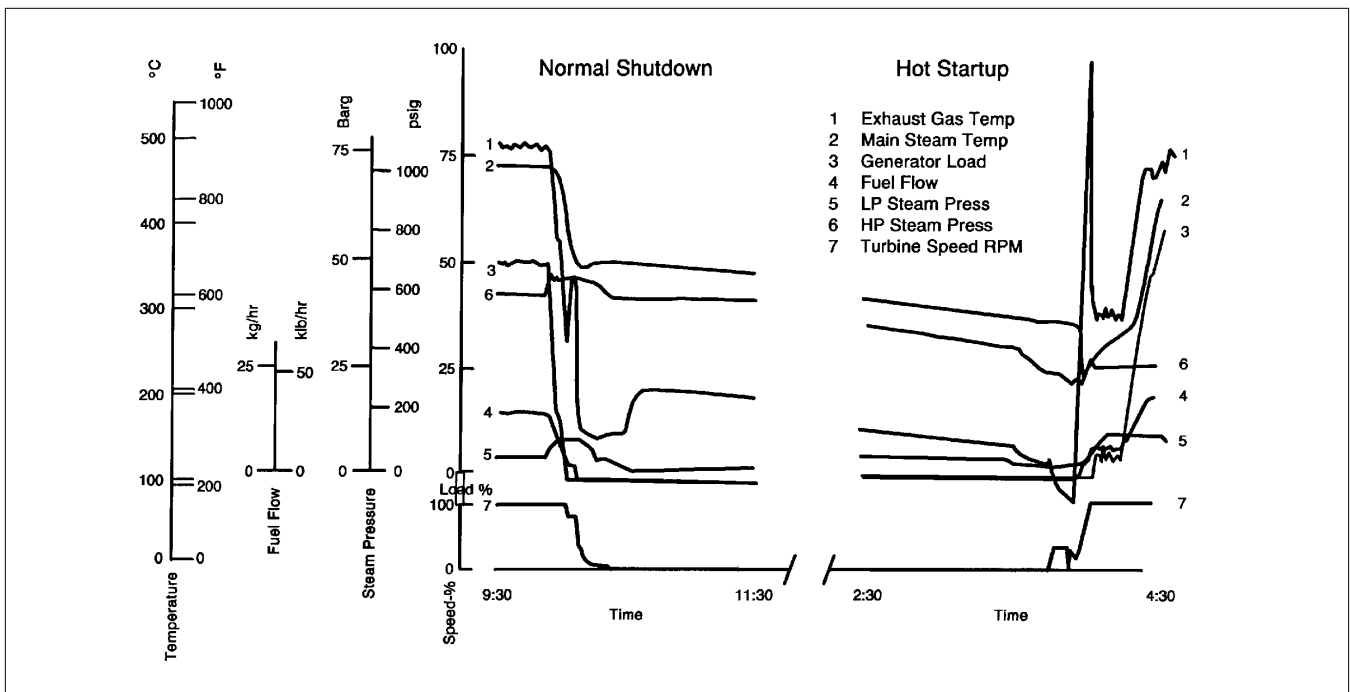
Combined-cycle plant operating information gathered through the GE user weekly log system for the Operation Reliability Analysis Program (ORAP) and information reported by the North American Reliability Council (NERC) depict an operating history characterized by high reliability and availability with a trend for continued reliabil-

ity improvement. Operating statistics from 1989 through 1995 for several utility power generation combined-cycle installations are summarized in Table 7. This data shows single-shaft combined-cycle systems achieve generally higher plant reliability and availability than multi-shaft combined-cycle systems. These excellent operating characteristics are the result of simplicity of control and operation and proper maintenance practices.

Operating data for the 14 STAG 109E units at the TEPCO Futtsu Station are shown on Table 8. This is an outstanding installation with excellent operation and maintenance practices, which enables the equipment to achieve outstanding operating results. The Japanese government requires a thorough inspection that is the equivalent of a major inspection at calendar intervals of two years. This impairs the availability, but enables reliability near 100%.

MAINTENANCE

Maintenance of single-shaft combined-cycles is performed on units individually, which does not impair the operation of other units in the station. This contrasts with multi-shaft combined-cycle units where steam turbine maintenance impairs the operation of several gas turbines. Operating intervals between maintenance on the components in single-shaft units are similar so that many planned maintenance activities can be performed



GT18541B

Figure 25. TEPCO Futtsu STAG 109E normal shutdown and hot start

**Table 7
STAG COMBINED-CYCLE PLANT SEVEN-YEAR OPERATING STATISTICS**

| STAG Configuration | Single-Shaft | | | | | | |
|------------------------|--------------|------|------|--------|------|------|------|
| Year | 1989 | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 |
| Plant Availability (%) | 87.5 | 90.5 | 92.3 | 83.1* | 87.5 | 91.8 | 93.8 |
| Plant Reliability (%) | 98.9 | 99.2 | 99.2 | 96.7** | 97.1 | 99.7 | 99.4 |
| Service Factor (%) | 61.1 | 40.3 | 36 | 34.0 | 35 | 37 | 36 |
| Sample Size | 10 | 10 | 10 | 10 | 10 | 10 | 10 |
| STAG Configuration | Multi-Shaft | | | | | | |
| Year | 1989 | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 |
| Plant Availability (%) | 87 | 88.7 | 92.3 | 89.0 | 88.9 | 83.9 | 89.7 |
| Plant Reliability (%) | 98.4 | 98.4 | 99.1 | 99.3 | 98.1 | 95.5 | 99.6 |
| Service Factor (%) | 47.7 | 41.3 | 41.8 | 56.6 | 42 | 44 | 41 |
| Sample Size | 20 | 21 | 22 | 30 | 30 | 28 | 28 |

* Major Inspection ** Generator Outage

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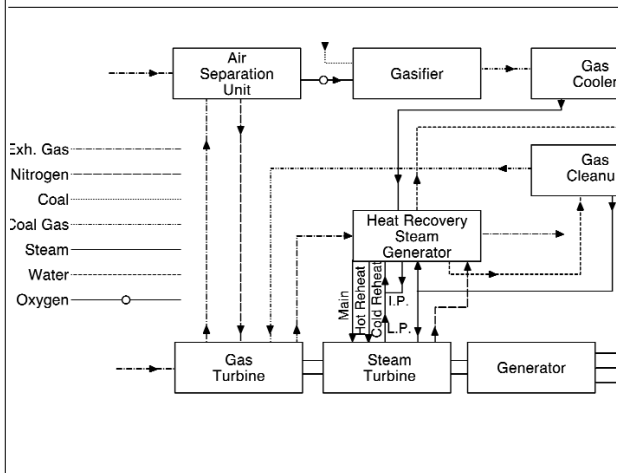
concurrently. The gas turbine combustion inspection interval is 8,000 hours which coincides with the annual HRSG inspection at one year intervals if base loaded or at two year intervals for mid-range peaking service (4,000 hrs/yr.). The hot gas path inspection on the gas turbine at 24,000 hours, which also includes a combustion inspection, coincides with an HRSG inspection. The major inspection of the gas turbine at 48,000 hours occurs at the recommended steam turbine major inspection, generator rotor removal and inspection, and HRSG annual inspection.

An example of the low maintenance cost

required by single-shaft STAG combined-cycle generation units is that of the three STAG 107E units at the Western Farmers Electric Coop Anadarko Station. These units have operated in mid-range peaking service and all have completed two maintenance cycles including two major inspections with the intermediate hot-gas-path, combustion and HRSG inspections. The average maintenance cost is 0.74 mills/kWh (Table 9).

Single-shaft STAG units with the generator between the gas turbine and steam turbine require removal of the steam turbine for generator rotor removal. The steam turbine has been

**Table 8
TEPCO FUTTSU STATION OPERATION
SUMMARY - MARCH 31, 1996**



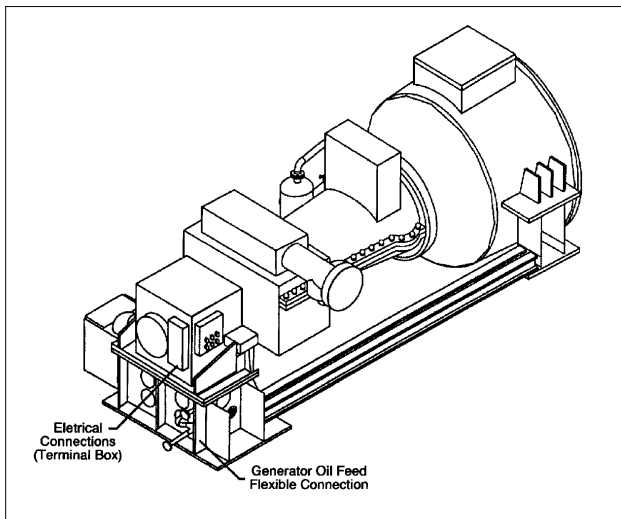
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**Table 9
WESTERN FARMERS - 3 STAG 107E
OPERATION AND MAINTENANCE DATA**

| | Plant Factor - % | Availability - % | Maintenance Mills/kWhr |
|---------|------------------|------------------|------------------------|
| 1978 | 55 | 72 | 0.35 |
| 1979 | 61 | 83 | 0.31 |
| 1980 | 75 | 93 | 0.31 |
| 1981 | 73 | 90 | 0.53 |
| 1982 | 32 | 97 | 0.66 |
| 1983 | 31 | 99 | 0.75 |
| 1984 | 55 | 98 | 0.41 |
| 1985 | 39 | 79 | 1.54 |
| 1986 | 45 | 81 | 0.92 |
| 1987 | 61 | 97 | 0.59 |
| 1988 | 44 | 93 | 0.92 |
| 1989 | 48 | 96 | 0.73 |
| 1990 | 53 | 93 | 1.11* |
| 1991 | 72 | 98 | 0.64 |
| 1992 | 76 | 89 | 1.38 |
| Average | 55 | 91 | 0.74 |

*Includes ~0.3 Mills/kWhr for Fuel Oil Retrofit
256,000 Total Operating Hours - Dec., 1992

GT23831



GT23819

Figure 26. Packaged base-mounted steam turbine

packaged and skid mounted to accommodate this requirement as shown in Figure 26. The exhaust is axial, all connections are flanged and the electrical connections are grouped at junction boxes. Appropriate jacking, pull points and rails in the installation enables the steam turbine to be easily moved without lifting.

PRODUCT STRUCTURE

The basic structure for the single-shaft STAG combined-cycle product line is the GE furnished Engineering Equipment Package (EEP). The EEP includes a unique combination of equipment and services such that the owner receives a plant performance guarantee and warranty of operation and serviceability of the combined-cycle system while retaining the capability to customize the plant design, auxiliaries, structures, etc. This is achieved by including in the GE scope the major combined cycle equipment which requires close coordination for assurance of meeting the performance objectives.

The equipment scope split between GE and the owner is shown in Figure 27 and the corresponding services and software split is presented in Figure 28. Key elements in the GE EEP scope are the combined-cycle equipment and system design and interface definition that enable the owner, his engineer, or engineer constructor to design the plant to satisfy his specific requirements.

COMPARISON WITH MULTI-SHAFT

The key advantage achieved by the single-shaft combined-cycle is its operating simplicity and

independence of unit operation and maintenance which results in high reliability and availability and low maintenance cost. Other differences, such as installed cost, are not as distinct and result in trade-offs that may be influenced by site requirements and owner operating requirements or preferences.

Installed Cost

The installed cost is approximately equal for multi-shaft and single-shaft systems; however, there are trade-offs that may influence a specific application. Also, there are differences between the non-reheat and reheat systems that result in different considerations regarding a comparison of installed

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

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Figure 27. 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 Installation Drawings
- Steady State and Dynamic Interface Definition
- Equipment Operation and Maintenance Installation
- Operation and Maintenance Training
- Construction and Operation Permit Support
- Performance and Environmental Test Support

Owner

- Construction and Operation Permits
- Plant Design
- Plant Construction
- Plant Startup, Commissioning and Operation
- Performance and Environmental Testing
- Site Preparation
- Project Administration

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Figure 28. Services and software scope split with Engineered Equipment Package

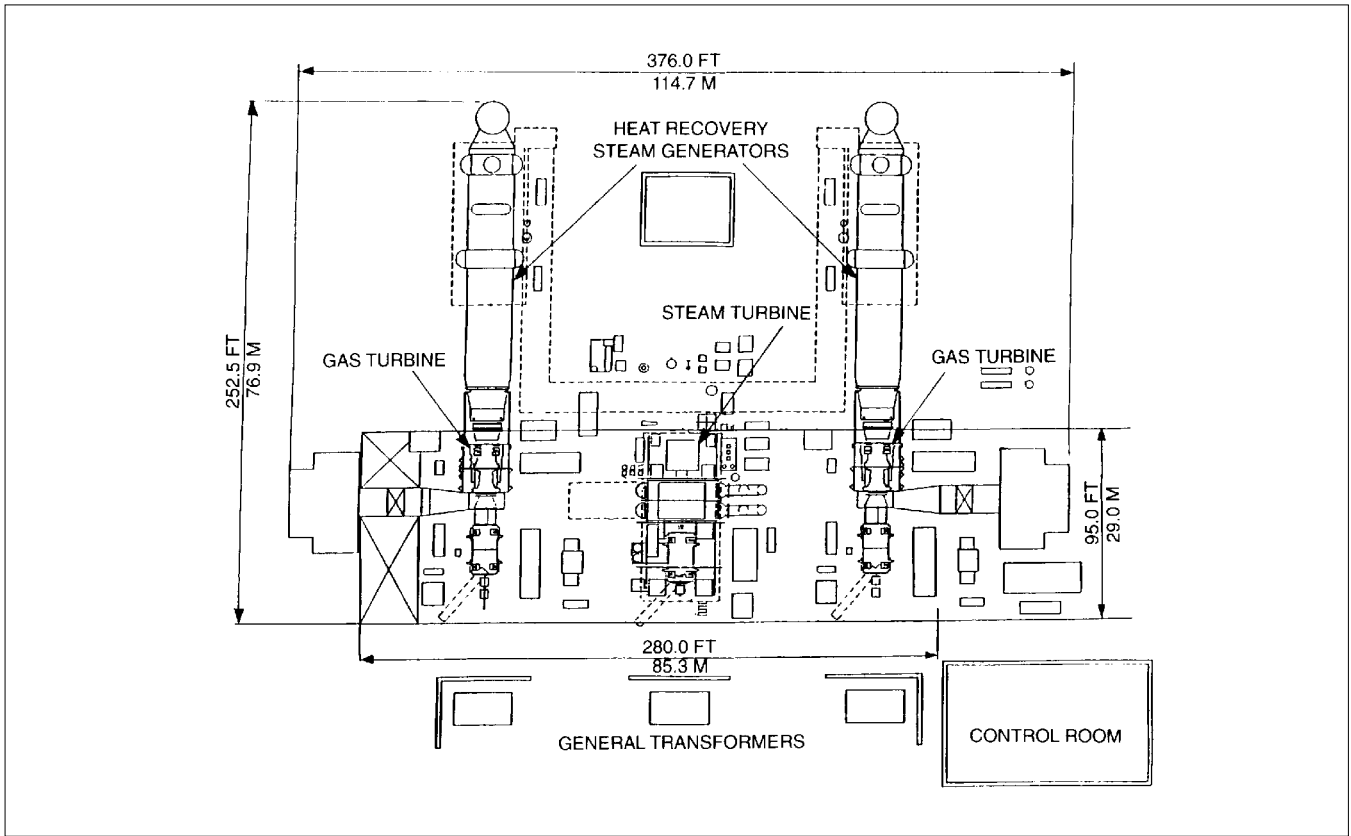


Figure 29. STAG 207FA multi-shaft combined-cycle equipment arrangement plan

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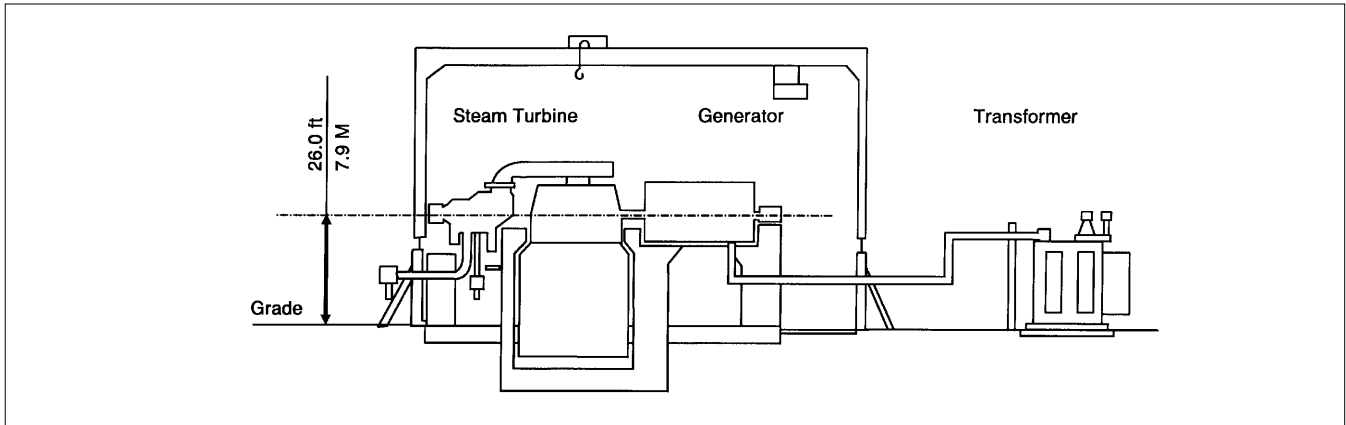


Figure 30. STAG 207FA multi-shaft combined-cycle steam turbine elevation

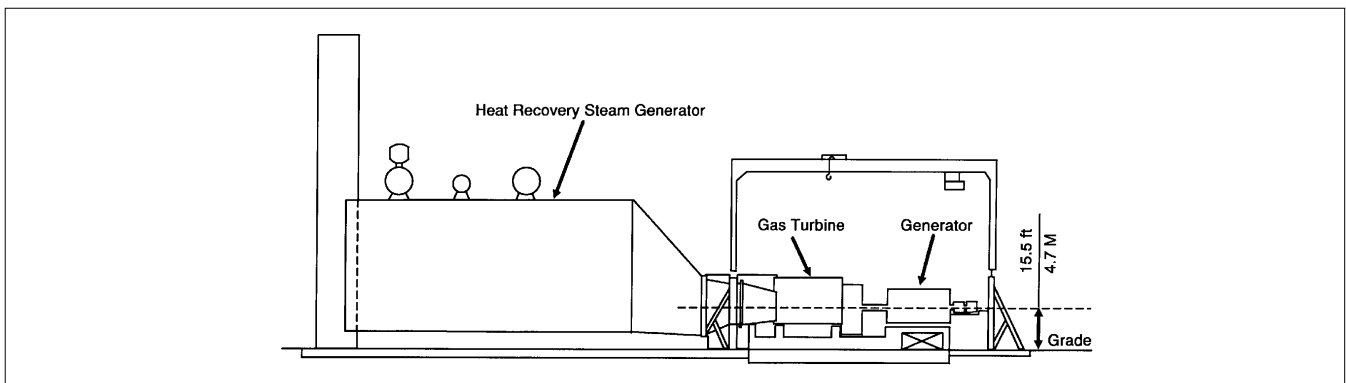
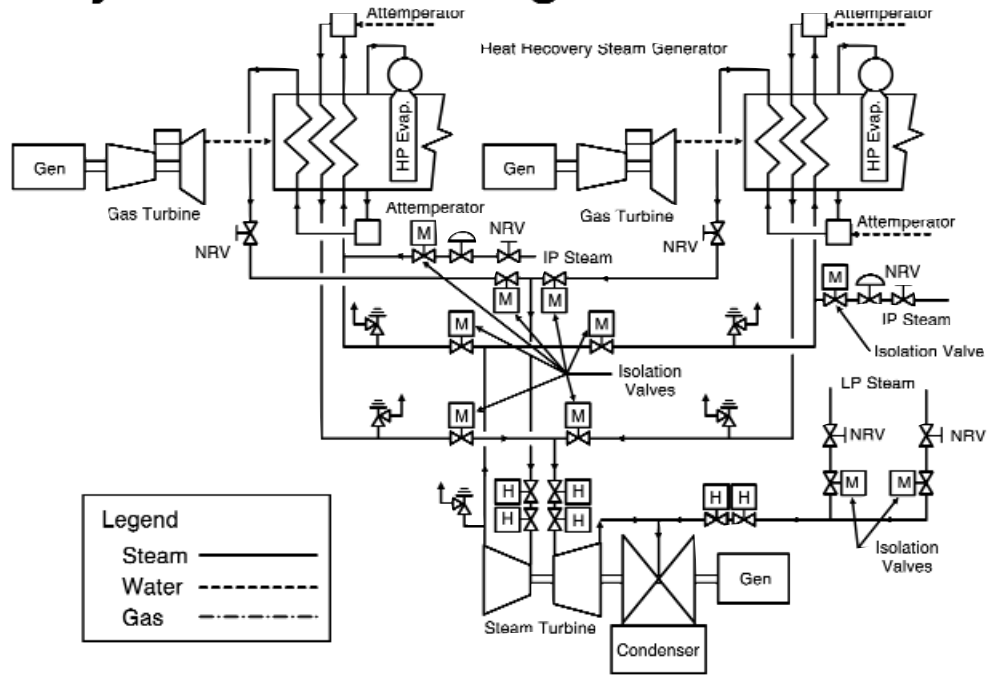


Figure 31. STAG 207FA multi-shaft combined-cycle gas turbine and HRSG elevation

GT23817

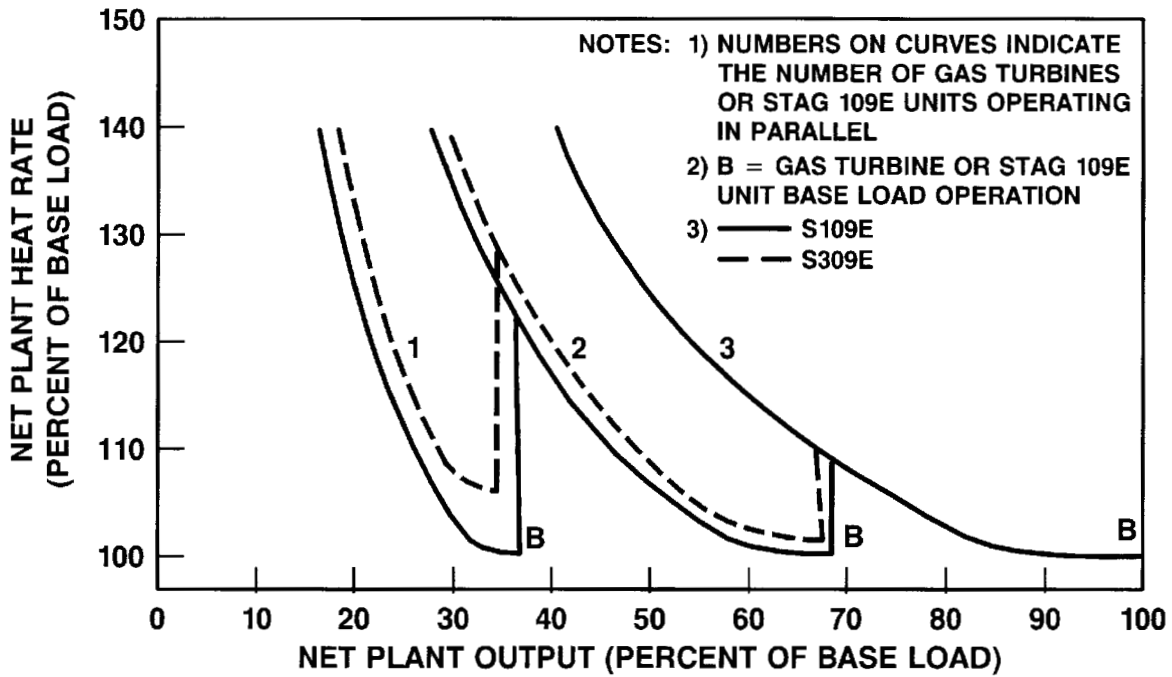
Steam Cycle Control Diagram



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Figure 32. Reheat multi-shaft combined-cycle steam cycle control diagram



GT23112

Figure 33. Combined-cycle system part load performance

Table 10
THREE-PRESSURE REHEAT COMBINED-CYCLE CONFIGURATION COMPARISON SUMMARY

| | STAG 107FA Single Shaft | Multi-Shaft | |
|--------------------------------|----------------------------|---------------------------|---------------------------|
| | | STAG 107FA (One GT/ST) | STAG 207FA (Two GT/ST) |
| Equipment (Quantity) | | | |
| - Gas Turbine | 2 | 2 | 2 |
| - Steam Turbine | 2 | 2 | 1 |
| - Condenser | 2 | 2 | 1 |
| - Cooling Water Trains | 2 | 2 | 1 |
| - Generators | 2 | 4 | 3 |
| - Main Electrical Connections | 2 | 4 | 3 |
| - Generator Transformers | 2 | 4 | 3 |
| Steam Valves (Quantity) | | | |
| - Main Steam Non-Return | 0 | 0 | 2 |
| - Reheat Isolation | 0 | 0 | 4 |
| - Reheat Balancing | 0 | 0 | 2 |
| - Reheat Relief | 0 | 4 | 5 |
| - Reheat Stop/Control | 0 | 2 | 1 |
| - Low Pressure Non-Return | 0 | 0 | 2 |
| Steam Headers | 0 | 0 | 5 |
| Foundations | High | High/Low | High/Low |
| Installed Cost | Low | High | Low |
| Operation | | | |
| - Combined Cycle | Simple | Simple | Complex |
| - Start/Stop | Simple | Simple | Complex |
| - Load Following | Good | Good | Good |
| - Contingency Management | Simple | Complex | Complex |
| - Islanding | Good | - | - |
| - Simple Cycle | No | Yes | Yes |
| Staged Construction | No | Yes | Yes |

GT23832

cost differences between multi-shaft and single-shaft combined cycles. The smaller non-reheat single-shaft systems can be installed on a slab type foundation at grade level so that their foundation cost is lower than the multi-shaft which would have a large pedestal mounted steam turbine. The larger reheat systems require a basement for the increased quantity of piping. The steam turbine is installed between the gas turbine and generator which requires a down exhaust to a condenser under the turbine. This requires the gas turbine, generator and steam turbine to be mounted on a pedestal whereas the gas turbine foundations can be lower in multi-shaft systems. Figures 29, 30 and 31 show the equipment arrangement drawings for a STAG 207FA system with a reheat steam cycle. The steam turbine pedestal is shown in Figure 30 while Figure 31 shows the lower foundation for the gas turbines.

Steam piping and valves are a major cost adder for the multi-shaft system. Figure 32 is a diagram of the major steam cycle piping showing the isolation valves, that are not required by the single-shaft system shown in Figure 23. Also, the length of steam piping is increased since the steam turbine is remote from the HRSGs for the multi-shaft systems. Figure 29 shows the arrangement with lowest cost steam piping. Longer steam piping runs result if both gas turbines and HRSG are located on the same side of the steam turbine.

The larger number of generators and main electrical connections also increase the cost of the system. Table 10 presents a comparison configuration summary for combined-cycles with three-pressure, reheat steam cycles. This chart illustrates qualitatively that the installed cost of the multi-shaft system with one gas turbine and steam turbine has the highest installed cost while the two gas turbine per steam turbine multi-shaft has approximately equal installed cost trade-offs. The operating simplicity favors the single-shaft.

Independent Operation of Gas Turbines

Operation of gas turbines independent of the steam system is a potential advantage that can be realized by the multi-shaft combined-cycle. However, this requires either exhaust gas bypass stacks and dampers, full steam bypass to the condenser, or full steam bypass to a separate dump condenser. All of these systems increase installed cost and operating complexity and reduce availability and reliability.

Performance

The heat rate of a multiple-unit, multi-shaft combined-cycle system will usually be slightly bet-

ter than that of a comparable multiple-unit single-shaft system. This small difference in heat rate is approximately 10 Btu/kWhr (10.5 kJ/kWhr) and results from higher efficiency of the larger high pressure section of the steam turbine. The part load heat rate of multiple single-shaft units is better than that of a multi-shaft system because of the reduced efficiency of the steam turbine at reduced steam flow. Figure 33 illustrates this difference.

CONCLUSION

Combined-cycle systems provide reliable and economic service in electric utility power generation applications. Flexibility in equipment selection and arrangement, thermal cycle, type of fuel, emission control and duty cycle enable optimization to meet a wide variety of owner requirements. Single-shaft combined-cycle systems offer further advantages as follows:

- Simplicity of single-unit control
- Low plant cost
- Minimum land area use
- Simplified control and operation with multiple pressure and reheat steam cycle
- High reliability and availability

Therefore, consideration of the single-shaft unit is recommended for all power generation combined-cycles that are installed in a single phase.

LIST OF FIGURES

- Figure 1. H technology single shaft combined-cycle unit
- Figure 2. Single-shaft, combined-cycle, three-pressure non-reheat steam cycle
- Figure 3. Single-shaft, combined-cycle, three-pressure reheat steam cycle
- Figure 4. Stag 107H/109H cycle diagram
- Figure 5. Ambient temperature effect on performance
- Figure 6. Typical single-shaft combined-cycle unit heat rate variation with power output
- Figure 7. Unitized IGCC system
- Figure 8. STAG 107EA, 109E configuration
- Figure 9. STAG 107EA steam turbine
- Figure 10. Large single shaft combined-cycle equipment configuration
- Figure 11. Two-flow reheat steam turbine
- Figure 12. STAG 107FA combined-cycle unit with single-flow steam turbine and gas turbine
- Figure 13. STAG 109FA perspective view
- Figure 14. STAG 109E equipment
- Figure 15. 2310 MW TEPCO Futtsu station – 14 STAG units
- Figure 16. Western Farmers Electrical Cooperative Plant
- Figure 17. STAG 107FA equipment arrangement plan
- Figure 18. STAG 107FA equipment arrangement elevation
- Figure 19. STAG 107FA elevation section through gas turbine
- Figure 20. 2800-MW TEPCO Yokohama Station
- Figure 21. Control configuration
- Figure 22. Typical control room layout
- Figure 23. Reheat single-shaft combined-cycle diagram
- Figure 24. Starting and loading characteristics
- Figure 25. TEPCO Futtsu STAG 109E normal shutdown and hot start
- Figure 26. Packaged base-mounted steam turbine
- Figure 27. Equipment scope split with Engineered Equipment Package
- Figure 28. Services and software scope split with Engineered Equipment Package
- Figure 29. STAG 207FA multi-shaft combined-cycle equipment arrangement plan
- Figure 30. STAG 207FA multi-shaft combined-cycle steam turbine elevation
- Figure 31. STAG 207FA multi-shaft combined-cycle gas turbine and HRSG elevation
- Figure 32. Reheat multi-shaft combined-cycle steam cycle control diagram
- Figure 33. Combined-cycle system part load performance

LIST OF TABLES

- Table 1 Single-shaft combined-cycle experience
- Table 2 Single-shaft STAG product line ratings
- Table 3 Single-shaft STAG combined-cycle base configuration
- Table 4 Product line nominal steam conditions
- Table 5 Single-shaft STAG product line equipment
- Table 6 Alternate single-shaft power plant design installed cost evaluation
- Table 7 STAG combined-cycle plant seven-year operating statistics.
- Table 8. TEPCO Futtsu station operation summary - March 31, 1996
- Table 9 Western Farmers – 3 STAG 107E operation and maintenance data
- Table 10 Three-pressure reheat combined-cycle configuration comparison summary

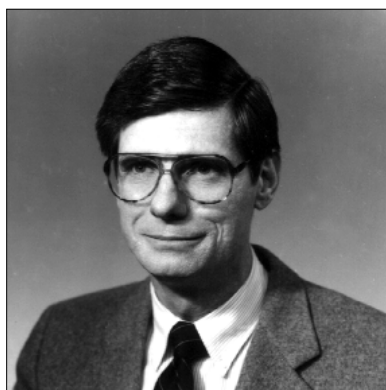


Leroy O. Tomlinson

Leroy O. Tomlinson is Chief Engineer of the Controls, Accessories and System Engineering Department in GE Power Generation Engineering. Responsibilities of this department include design and development of gas turbine and steam turbine controls, electrical systems, accessories and fluid systems and gas turbine and combined cycle system engineering.

Leroy has held engineering management assignments in GE for 23 years, including Gas Turbine and Combined-Cycle Application Engineering and Power Plant Systems Engineering and he has 42 years of engineering experience in gas turbine and combined-cycle power generation equipment and plant design, test, application and operation.

Mr. Tomlinson is active on several ASME Gas Turbine and Power Test Code committees. He is a registered engineer in Pennsylvania, Florida and Texas.



Sean McCullough

Sean McCullough is Manager of Reference Plant and Standards Development in the Global Power Plant Systems Department. He is currently responsible for leading efforts to reduce proposal, engineering, and construction cycle and cost, through the development of Reference Plant Designs and Constructability Initiatives.

Sean holds a degree in mechanical engineering, is a licensed professional engineer, and recipient of the Power System's Engineering Awards in 1985 and 1994. He also holds two patent awards. Since joining GE in 1972, he has held a variety of positions including Start-up Engineer, Design Engineer, Service Manager, and Project Manager.