Mitsubishi F Series Gas Turbine Combined Cycle Operating Experience

M.Ishikawa, S.Uchida, K.Okada
Mitsubishi Heavy Industries, Ltd. Power Systems Headquarters
K.Hiramoto, Xu XiuFu,
Mitsubishi Heavy Industries, Ltd. Takasago Machinery Works

Abstract

The construction of power plants with high thermal efficiency has recently become more important than before in countries throughout the world from the view point of energy resource saving and global environmental conservation. Especially, advanced combined cycle power plants are attracting attention due to their higher thermal efficiency. Mitsubishi Heavy Industries, Ltd. has installed large capacity and high efficiency combined cycle plants since the unit No.3 in the Higashi Niigata Thermal Power Station started commercial operation in 1985 with the ‘D’ series engine which had a firing temperature of 1150 degree C. More than 50 units have been constructed as shown in Figure 1.

The ‘F’ series engine which has a firing temperature of 1350-1400 degree C, is now predominant in the current market with the remarkable improvements in the gas turbine technology. Through the operating experiences of ‘F’ series engine for more than 10 years, MHI has performed the improvement of higher reliability and availability, higher plant performance, and operation flexibility utilizing latest technology for GT, HRSG, ST, and control system. As a result, 40 units have been constructed, and more than 1,200,000 hours operation for the ‘F’ series gas turbines and the combined cycle efficiency of 55-57%(LHV) have been achieved.

In this paper, the design features and optimization of combined cycle plants with ‘F’ series engines and their operating experiences are presented.

Figure 1　Mitsubishi Combined Cycle Plants in the World

Table 1 Specifications of Mitsubishi Combined Cycle Plants Using 'F' Series Gas Turbine

No.	PLANT NAME	OUTPUT (MW)	Commercial Operation	FUEL	PLANT TYPE
1	Florida Power & Light Lauderdale (USA)	914	1992	Natural Gas/Distillate Oil	M501F 2on1 x 2
2	Kyushu Electric Shin-Ohita #2-1/2 (Japan)	870	1994/1995	Vaporized LNG	M501F 1on1 x 4
3	Kansai Electric Himeji #5 (Japan)	670	1995	Vaporized LNG	M501F 3on1 x 1
4	Chubu Electric Chita #1/2 Repowering (Japan)	529 x2	1995/1996	Vaporized LNG	Repowering
5	Chubu Electric Kawagoe #4 (Japan)	1650	1997	Vaporized LNG	M501F 1on1 x 7
6	EGAT Wang Noi Phase I (Thailand)	1305.8	1997	Natural Gas/Distillate Oil	M701F 2on1 x2
7	Tokyo Electric Chiba #1 (Japan)	1440	1998	Vaporized LNG	M701F 1on1 x 4
8	EGAT Wang Noi Phase II (Thailand)	122.75	1998	Natural Gas/Distillate Oil	M701F 2on1ｘ1
9	Empresa Electrica San Isidro (Chile)	370	1998	Natural Gas/Distillate Oil	M701F 1on1 x 1
10	TEAS Bursa (Turkish)	1400	1999	Natural Gas	M701F 2on1 x 2
11	Central Costanera S.A. Costanera (Argentina)	830	1999	Natural Gas/Distillate Oil	M701F 2on1 x 1
12	Entergy Saltend (UK)	1200	2000	Natural Gas	M701F 1on1 x 3
13	CFE Chihuahua (Mexico)	450	2001	Natural Gas/Distillate Oil	M501F 2on1 x 2
14	EVN/Phu My 1(Vietnam)	1,090	2001	Natural Gas/Distillate Oil	M701F 3on 1 x 1
15	Entergy Damhead Creek(England)	800	2001	Natural Gas	M701F 2on 1 x 1
16	AES Parana (Argentina)	740	2001	Natural Gas/Distillate Oil	M701F 2on 1 x 1
17	PPN(India)	360	2001	Natural gas/Naphtha	M701F 1on 1 x1
18	Tuas Power PTE Ltd(Singapore)	736	2001	Natural Gas/Distillate Oil	M701F1on 1 x 2
19	FET TUXPAN Ⅱ (Mexico)	495	2001	Natural Gas/Distillate Oil	M501F 2on1 x 1
20	EDF ALTAMILAⅡ(Mexico)	503	2002	Natural Gas/Distillate Oil	M501F 2on1 x 1
21	TPC NAN-Pu(Taiwan)	248	2002	Natural Gas	M501F 1on1 x 1
22	Azer Energy SEVERNAYA(Azerbaijan)	395.2	2002	Natural Gas/Distillate Oil	M701F 1on1 x 1
23	Trans Alta CHAMPECHE(Mexico)	260	2003	Natural Gas/Distillate Oil	M501F 1on1 x 1
24	NPR.Negishi (Japan)	431	2003	Synthetic Gas / Kerosene	M701F 1on1 x 1
25	Union Fenosa TUXPANⅢ＆Ⅳ(Mexico)	498.4x2	2003	Natural Gas	M501F 2on1 x 2 x 2
26	Undisclosed (Spain)	390x3	2003	Natural Gas/Distillate Oil	M701F 1on1 ｘ 3
27	Undisclosed (USA)	793.4	2003	Natural Gas/Distillate Oil	M501F 3on1 x 2
28	Port Dickson (Malaysia)	730	2004	Natural Gas/Distillate Oil	M701F 2on1 x 1
29	Lamma No.9 (Hong Kong)	376	2004	Natural Gas/Distillate Oil	M701F 1on1 x 1

Introduction

Several heat recovery type combined cycle systems have been installed using the ‘F’ series gas turbines since 1992, all over the world. As shown in Table 1, 40 plants are in operation, and 8 plants are currently under test operation. In addition, 7 plants are being under manufacturing and/or construction.

Mitsubishi combined cycle plants have good reputations from all customers with its high efficiency, high reliability, high availability and flexible operation incorporating the customers’ practices and preferences.

Main features of the plant

The overall configuration of one unit is shown on Figure 2

1) In order to increase the total thermal efficiency, a heat recovery cycle using a gas turbine with a high efficiency is selected.
2) AS the gas turbine inlet temperature directly influences its thermal efficiency, firing temperature of 1350 deg C (It was uprated to 1400 deg C.) was adopted with advanced cooling of rotating blades and stationary vanes etc. Thus, the metal temperature could be maintained as the same level of ‘D’ series of gas turbine.
3) According to the increase of the GT inlet temperature, a premixed combustor system was further developed to obtain low NOx without injecting water and steam to satisfy the environmental requirements, and the advanced cooling technology enabled the combustor wall metal temperature to be lowered.
4) The gas turbines are capable of both single fuel firing(fuel gas) and duel fuel firing(fuel gas and fuel oil).
5) In order to recover the gas turbine exhaust heat with small heat loss, the heat recovery steam generators are of triple pressure type generating high, medium and low pressure steam with natural circulation.
6) The steam turbine is also triple pressure type with high thermal efficiency and low heat loss adapting the ISB (Integral Shroud Blade) to the LP last blades. Partial load efficiency is further improved by variable pressure operation over a wide load range.
7) An integrated digital computer control system which has the distributed hierarchical function is installed to control the plant as a whole, to meet the requirements of flexible and optimum operation for combined operation of GT, ST

and HRSG.

8) A combined cycle plant is composed of two or more generators. Selection of main circuit system for generator is an important factor in plant reliability, equipment layout and economy. The plant employs a low-voltage synchronous closing system with GMCB in the generator main circuit instead of a high-voltage synchronous system for the purpose of the deletion of starting transformer and the reduction of number of switchyard bays.
9) The design and construction of the facility shall be suitable for continuous base load operation and for intermittent or partial load operation at a constant or fluctuating level, and DSS (Daily Start & Stop) operation.

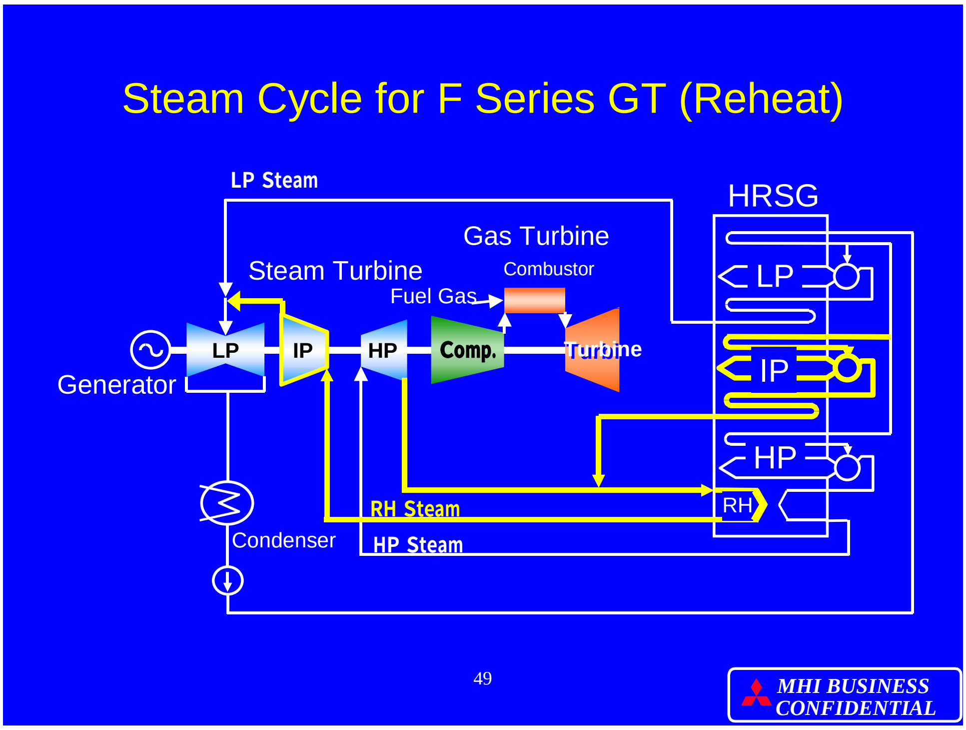


Figure 2 Overall configuration of 'F' series Combined Cycle Plant

Optimization of combined cycle plant design

The combined cycle plant system will be so designed and optimized considering a lot of factors such as the site condition, performance, operability, controllability, space availability, maintenance, and economical cost.

1) The optimum bottoming cycle will be selected to attain the maximum thermal efficiency by recovering the heat effectively from the exhaust gas of 'F' series gas turbine. Optimization of the plant cycle resulted in the selection of a superheat/reheat and low pressure cycle (Triple pressure system), and the steam pressure and temperature are determined considering the limitation of steam pressure requirement for natural circulation of HRSG, and the erosion on ST LP last blades (the wetness fraction of steam shall be less than 12 %.)
2) Depending on the combination of turbines and generators, system can be classified into two. i.e. single shaft type in which a gas turbine is directly coupled to a steam turbine with a single common generator, and multiple shaft type in which a gas turbine and steam turbine are coupled to its own generator respectively. Considering base load operation of the plant, the multiple shaft type is a little bit more efficient than a single shaft type. The single shaft heat recovery combined cycle type was selected, because it is suitable for daily start and stop (DSS) operation. The single shaft configuration with flexible coupling and/or SSS clutch can also be applied. The comparison table between two kinds of shaft configuration is shown on Figure 3
3) Depending on volume flow of steam turbine and achievable condenser vacuum, the steam turbine is selected from double cylinder type and single cylinder type with the corresponding last blades. (Refer to Figure 4.)

   An axial flow and down flow type steam turbine can be selected according to the requirements of total plant arrangement and economical reasons.
4) Depending on the starting capacity of GT and availability of auxiliary steam, the starting method is selected from the following three items.
   - Starting Motor
   - Steam Turbine
   - Static Frequency Converter (SFC)
5) HRSG pinch point can be optimized by evaluating the total equipment cost and running cost (fuel cost) for the variation of the pinch point. Small pinch point

requires large heating surface and result in higher C/C efficiency. Pinch point optimization is the trade-off between construction cost and operating cost. (Refer to Figure 5)

6) The Vertical and horizontal gas flow type HRSG can be selected according to the site occupied area and economical cost.
7) The following four types of condenser cooling system is adopted according to a site condition such as the availability of a large amount of cooling water and environmental requirement at site.
    - Once through cooling
    - Wet Cooling Tower
    - Dry Cooling Tower
    - Air Cooled Condenser
8) In order to prevent HRSG economizer tubes from corrosion, feed water temperature should be raised above water dew point (around 60 deg. C) and sulfuric acid dew point. (around 100 deg. C) If the plant is designed for duel fuel, we have to be careful for the need of installing deaerator for preventing sulfuric acid corrosion while distillated oil is fueled, as well as the need for preheater recirculation system for preventing carbonic acid corrosion while natural gas is fueled.

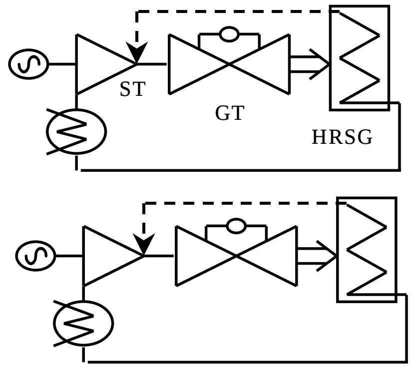
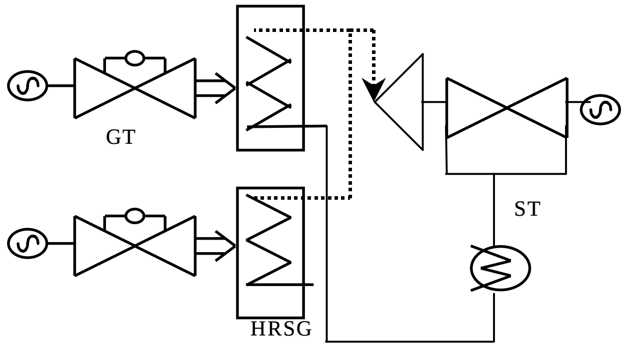
SINGLE SHAFT (1GT - 1HRSG - 1ST) x 2	MULTIPLE SHAFTS (2GT - 2HRSG - 1ST)
	
Suitable for DSS (Daily Start & Stop) & BASE load application Shorter start-up time	Suitable for BASE load pplication Higher thermal efficiency at base load
Auxiliary steam (approx. 30 t/h) for ST cooling is required during start-up.	Less Auxiliary Steam Consumption during Start-up (approx. 3 t/h)
Simple Operability	GT Simple cycle operation is available with bypass stack
Much Coordination in GT&ST Design Work	ST design work can be separated from GT

Figure 3 Comparison between Single Shaft and Multiple Shaft

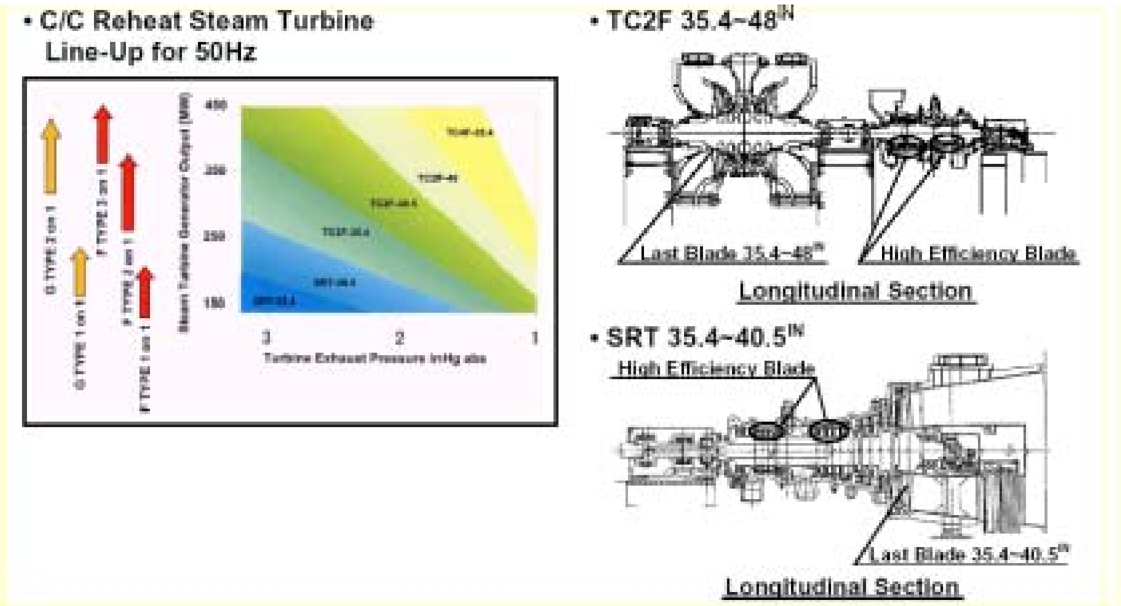


Figure 4 Mitsubishi C/C Reheat Steam Turbine Line-up

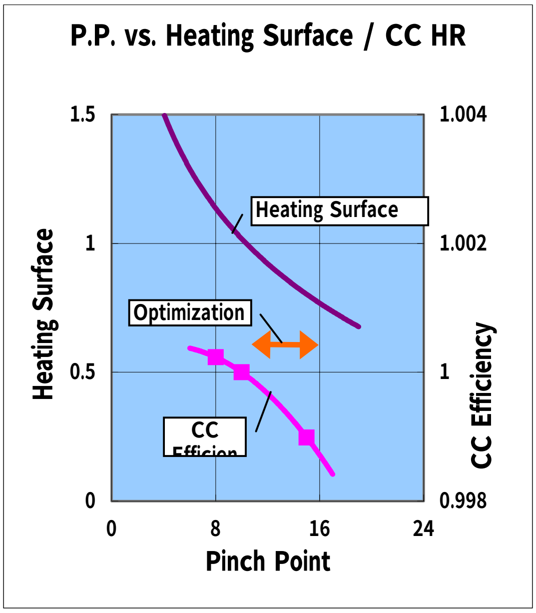


Figure 5 Optimization of HRSG

Plant performance and equipment specifications

The power output of a gas turbine varies substantially with the ambient temperature. It is therefore necessary to select the plant output so that it will be adequate under all normal operating conditions.

The performance of each of M501/701F gas turbine and its C/C plant is shown in Table 2.

Table 2 Performance Data of M501F/M701F gas turbine and its C/C plant

Model of GT	M501F	M701F
Rated speed	3600rpm	3000rpm
Rated Output	185MW	270MW
Efficiency	37.0 %	38.2 %
Kind of fuel	Natural gas	Natural gas
1) Turbine		
Type	Axial Flow Type	Axial Flow Type
No. of stages	4	4
Turbine Inlet Temperature	1400 deg. C	1400 deg. C
2) Compressor		
Type	Axial Flow Type	Axial Flow Type
No. of stages	16	17
No. of Bleed	3	3
Air Flow	453 kg/sec	651 kg/sec
3) Combustor		
Type	Multi-can-annular type	Multi-can-annular type
No. of combustor	16	20
C/C Plant (1 on 1)		
Rated Output	280 MW	398 MW
Efficiency	56.7 %	57.0 %
C/C Plant (2 on 1)		
Rated Output	564 MW	800 MW
Efficiency	57.0 %	57.3 %

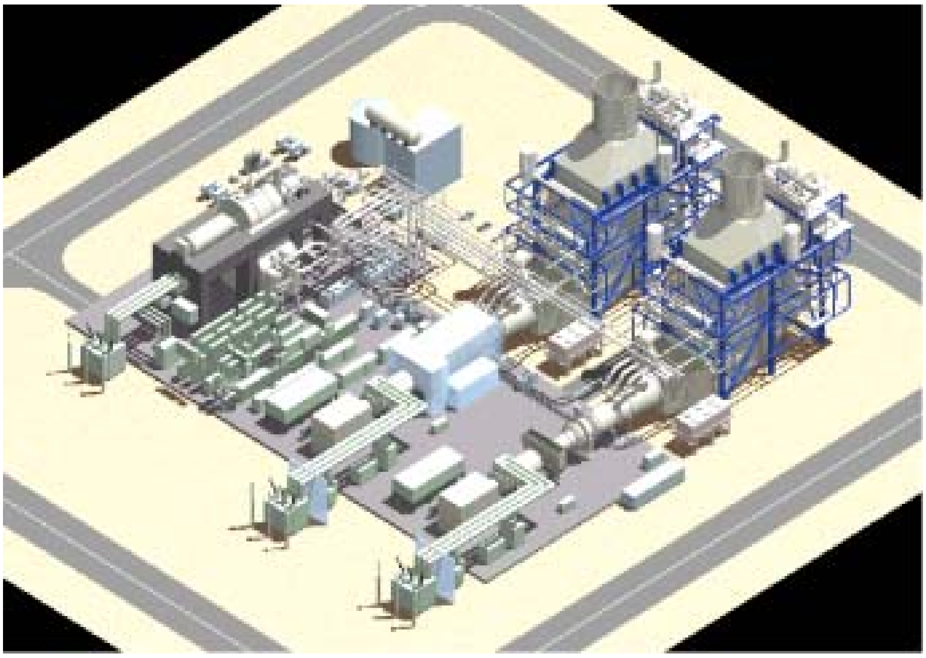
Optimum Layout of System

The plant arrangement should be examined so that the land and facilities will be so optimizedly arranged.

The generation plant arrangement is designed based on the following design concepts.

1) The optimum arrangement of equipment will be determined by considering functional requirement, economy of piping and electrical cable, economy of equipment supports, installation and maintenance access requirements, ventilation requirements and equipment generated noise and vibration.
2) The overall arrangement will provide adequate space for operation, maintenance and construction.
3) Maintenance space has been provided so that disassembly, inspection, and maintenance can be carried out on a unit even while an adjacent unit is operating
4) The plant arrangement will be mainly influenced by the following factors, which shall be definitely fixed at the beginning of the design stage.
   - Shaft configuration of power train
     (Single shaft or Multi shaft, and 1 on 1 or 2 on 1 or 3 on 1)
   - Outdoor or indoor installation
   - Type of steam turbine
     (Single or double cylinder and axial flow or down flow)
   - Type of condenser cooling system
     (Location of circulating water intake/outfall and location of cooling tower)
   - Electrical interface of transmission lines
     (Location of switchyard)
5) The common equipment related to GT simple cycle operation shall be so designed to locate as near as possible to GT and its auxiliaries so that they are constructed and commissioned at the same time in case of GT simple cycle operation.
6) Enough space for routing major steam piping and cable shall be considered around GT area so that they may not interfere with the inlet duct of GT inlet air filter in case that the single shaft configuration should be adopted.
7) The attached Figure 6 and 7 show bird's eye view and general arrangement of the typical power block. All of the gas turbines and steam turbines are installed in the main turbine building with enough open space for disassembly during overhaul inspections.

   The gas turbines are parallel to one another in the turbine building, and HRSGs are located outdoors in series with the gas turbines.



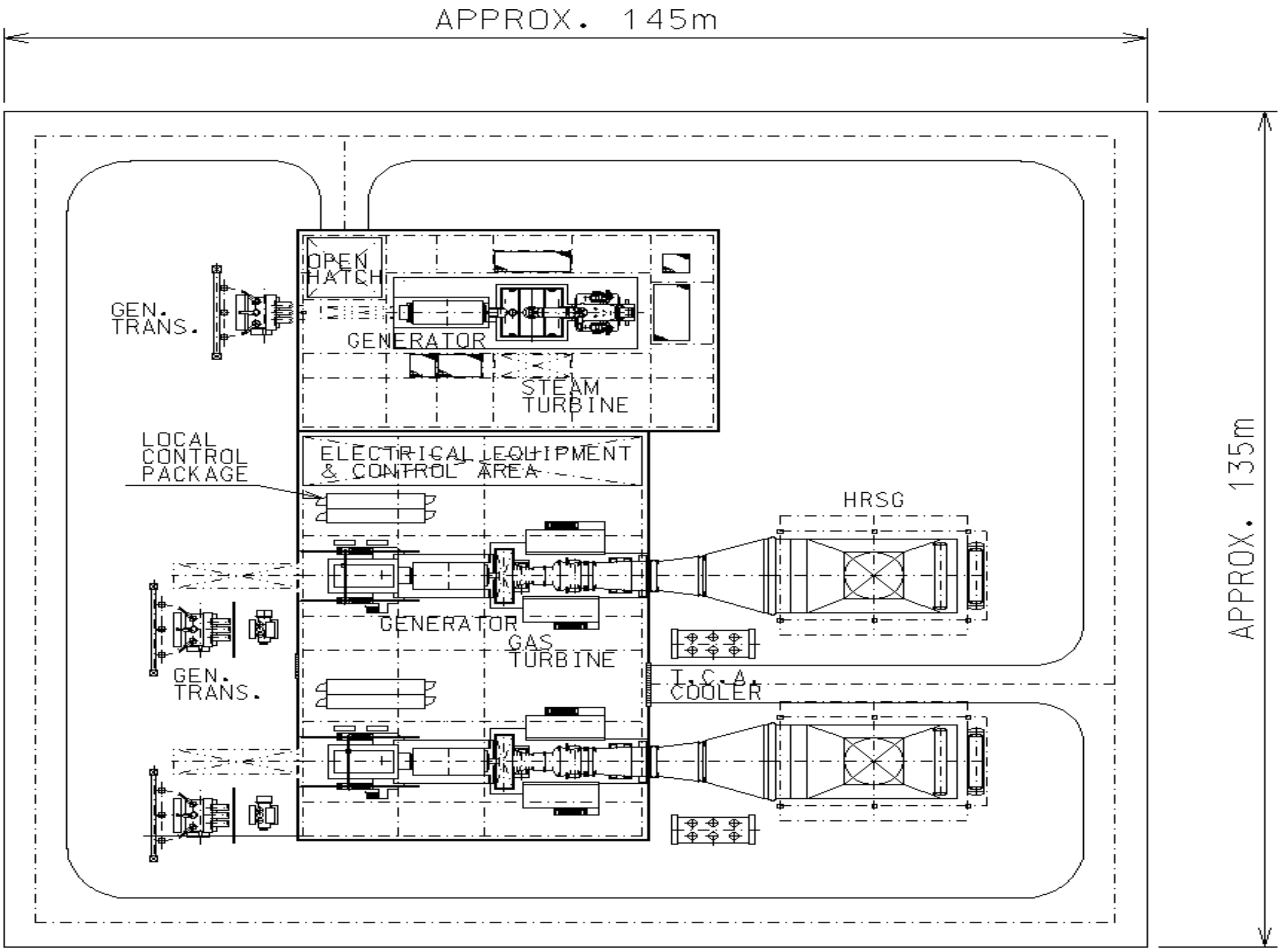


Figure 6 General Arrangement of Multiple Shaft C/C Plant

Figure 7 General Arrangement of Multiple Shaft C/C Plant

Operation and Plant Control System

1) Major features of combined cycle control system

In combined cycle plants which consist of several numbers of major equipment such as GT, ST, HRSG and Generator, it is necessary to control total plant equipment synthetically, coordinating the different characteristics between the major equipment. The major features of combined cycle control system are as shown below.

(1) Coordinated control between major equipment

(2) CRT based operation and monitoring for plant total supervision

Process systems and equipment will be adequately monitored to provide operators with all information required for safe and easy operation of the plant.

(3) Flexible automatic control system considering various operation patterns

Automatic operation is to be performed by distributed control system under normal operation and plant start up/shut down operation.

Start/stop operation for plant auxiliaries can also be possible by using CRT operator station. however manual controls will also be provided to allow manual operation or manual intervention of the automatic process.

(4) Optimized control system achieving highly efficient operation

In a combined cycle power plant which employs several gas turbines, it is possible to assure the high plant thermal efficiency by changing the number of operating gas turbines according to the power demand

(5) Plant load control following load demand signals from remotely and locally

(6) Distributed independent control system for each major equipment for the purpose of risk dispersion

(7) Redundant control system with high reliability

As a general principle, the failure of no single item of plant, shall result in the complete loss of station electrical output. Plant failures may result at most in a reduction of electrical output.

(8) Independent plant interlock system in case of emergency

All plant equipment and systems control shall be achieved by Distributed Control System (DCS), local control systems which interface with DCS, stand alone control systems and hard-wired circuits.

The majority of plant equipment control and information functions will be implemented in DCIS. The DCIS also provides control, status and alarm interfacing with non-DCIS controlled system.

The control system shall allow the plant to be controlled by one control room operator, one shift supervisor and a roving plant operator although more people will be required at busy times.

2) Operation Flexibility

The control system shall be designed to enable the power station to safely respond to partial and full load and continue generation on house load in the case of station load rejection.

In addition, the facility can be so designed to enable the following operations when requested by the customer.

(1) GT simple cycle operation with bypass stack
(2) Black out start up with black start facility
(3) Duct burner system with supplemental firing system to obtain larger electrical output
(4) Inlet air cooling system with evaporative cooler or fog system to obtain larger electrical output in case of higher ambient temperature
(5) Change-over operation from fuel gas firing to fuel oil firing in case of low fuel gas pressure.
(6) Two shift operation such as DSS (Daily start &stop) operation
The typical operating record of DSS operation is shown in Figure 8.

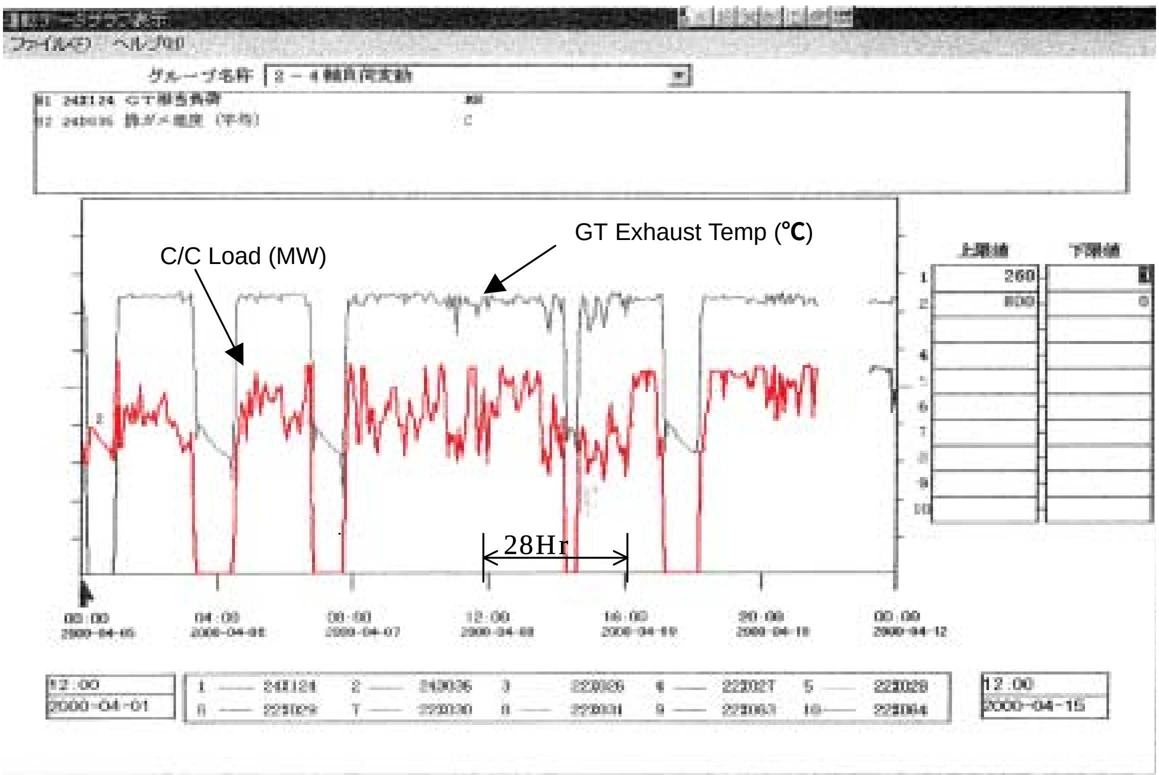


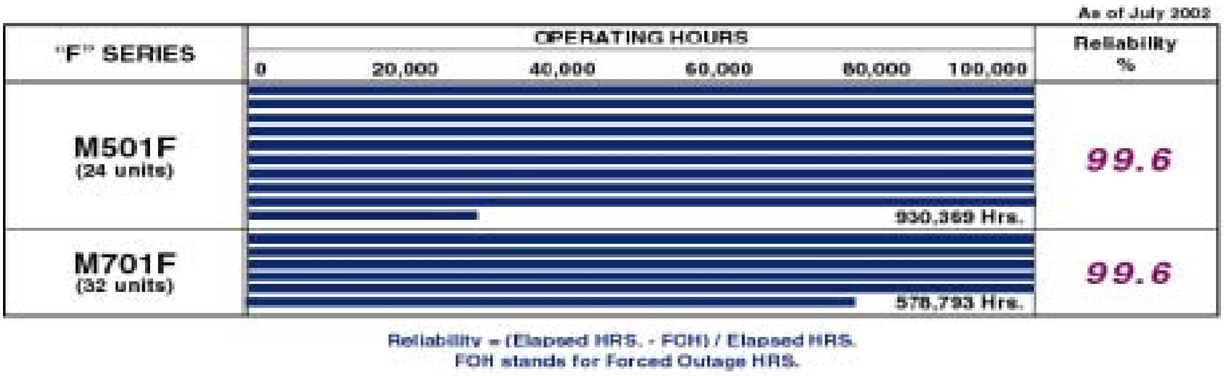
Figure 8 Sample Operation Record 'F' Series Single Shaft C/C Plant

Project Operation Availability

Table 3 & 4 show operating experiences of 501F & 701F gas turbines, which can enable us to recognize how Mitsubishi gas turbines are so reliable.

Fleet reliability of F series gas turbine as of July, 2002 is 99.6% for M501F 24units for 930,369 operating hours cumulative and 99.6% for M701F 32 units for 578,793 operating hours cumulative as shown below.

Reliability is defined as the balance of possibility of forced outage.



In addition, Mitsubishi's recent operating experience in Chihuahua M501F combined cycle plant with 2 on 1 multi shaft configuration in Mexico(Figure 9). Its electrical output is 445MW(GT:144 MW x 2, ST: 160MW) and entered into commercial operation in 2001.

This plant is being so reliable that the customer of CFE (Comision Federal de Electricidad) gave a reward as the high reliability power plant, and 'Best Power Plant' prize was awarded from the journal of 'Diesel & Gas turbine'.

Figure 9 Chihuahua Power Station

Table 3. Operating Experience of M501F Gas Turbine

As of July 2002

	CUSTOMER SITE	TYPE F	TYPE F3	No.of UNIT GT+ST	OUTPUT	STATUS OF OPERATION ('93 – 2002)	OPE. HRS	START& STOP
M501F (60Hz)	OVERSEAS 1	O		(2+1)×2	900 MW		* 246,490	* 633
	DOMESTIC 1	O		(1+1)×4	870 MW		188,718	5,582
	DOMESTIC 2	O		3+1	670 MW		149,140	1,347
	DOMESTIC 3	O		(1+1)×2	529 MW		82,708	359
	DOMESTIC 4	O		(1+1)×7	1,700 MW		222,147	3,040
	OVERSEAS 2		O	2+1	435 MW		26,689	247
	OVERSEAS 3		O	2+1	498 MW		** 8,674	** 131
	OVERSEAS 4		O	1+0	197 MW	Commercial ops 2002		
	OVERSEAS 5		O	2+1	500 MW	Commercial ops 2002		
	OVERSEAS 6		O	2+1	503 MW		5,803	143
	OVERSEAS 7		O	(1+0)x3	591 MW	Commercial ops 2002		
	OVERSEAS 8		O	2+1	500 MW	Commercial ops 2003		
	OVERSEAS 9		O	(2+1)x3	1,500 MW	Commercial ops 2003		
	OVERSEAS 10		O	1+1	248 MW	Commercial ops 2003		
	OVERSEAS 11		O	1+1	263 MW	Commercial ops 2003		
	OVERSEAS 12		O	2+1	500 MW	Commercial ops 2003		
	OVERSEAS 13		O	2+1	450 MW	Commercial ops		
	OVERSEAS 14		O	2+1	480 MW			
	OVERSEAS 15		O	(2+1)x2	960 MW			
	OVERSEAS 16		O	(3+1)x3	2,729 MW			
	OVERSEAS 17		O	(2+1)x2	1,000 MW			
	OVERSEAS 18		O	2+1	500 MW	Commercial ops 2005		
	GT SUB TOTAL			67		SUB TOTAL	930,369	11,482

Running : 24 Units
Booked Order : 43 Units

▭ TRIAL OPERATION
▬ COMMERCIAL OPERATION

* As of Oct. 2001, ** As of May. 2002

Table 4. Operating Experience of M701F Gas Turbine

As of July 2002

	CUSTOMER SITE	TYPE F	TYPE F2	TYPE F3	No.of UNIT GT+ST	OUTPUT	STATUS OF OPERATION ('93 – 2002)	OPE. HRS	START& STOP
M701F (50Hz)	K-POINT*	O			1+0	149 MW		3,564	621
	OVERSEAS 1	O			(2+1)×2	1,300 MW		143,005	1,865
			O		2+1	720 MW		49,989	844
	OVERSEAS 2	O			1+1	370 MW		25,442	107
	OVERSEAS 3			O	2+1	830 MW		44,622	465
	DOMESTIC 1	O			(1+1)×4	1,440 MW		82,383	1,123
	OVERSEAS 4	O			(2+1)×2	1,400 MW		100,016	352
	OVERSEAS 5			O	(1+1)×3	1,200 MW		46,291	309
	DOMESTIC 2			O	1+1	430 MW	Commercial ops [illegible]		
	OVERSEAS 6			O	1+1	350 MW		6,249	68
	OVERSEAS 7			O	2+1	800 MW		25,156	236
	DOMESTIC 3			O	1+1	300 MW	Commercial ops [illegible]		
	OVERSEAS 8			O	3+1	1,090 MW		20,736	280
	OVERSEAS 9			O	1+1	365 MW		9,533	121
	OVERSEAS 10			O	(1+1)×2	720 MW		13,193	74
	OVERSEAS 11			O	2+1	830 MW		** 8,614	** 142
	OVERSEAS 12			O	1+1	400 MW	Commercial ops [illegible]		
	OVERSEAS 13			O	(1+1)×3	1,200 MW			
	OVERSEAS 14			O	2+1	750 MW			
	OVERSEAS 15			O	1+1	300 MW			
	OVERSEAS 16			O	(1+1)×2	720 MW			
	OVERSEAS 17			O	2+1	750 MW			
	OVERSEAS 18			O	1+1	414 MW			
	GT SUB TOTAL				46		SUB TOTAL	578,793	6,807

Running : 32 Units
Booked Order : 14 units

▭ TRIAL OPERATION
▬ COMMERCIAL OPERATION

* State regulations requires that:
The operation for one year should be within 720 hrs.

** As of June 2002

Project schedule

The figure 10 shows the typical project schedule for the large combined power plant.
It will take approximately 28 months from the commencement of design work to the commercial operation,

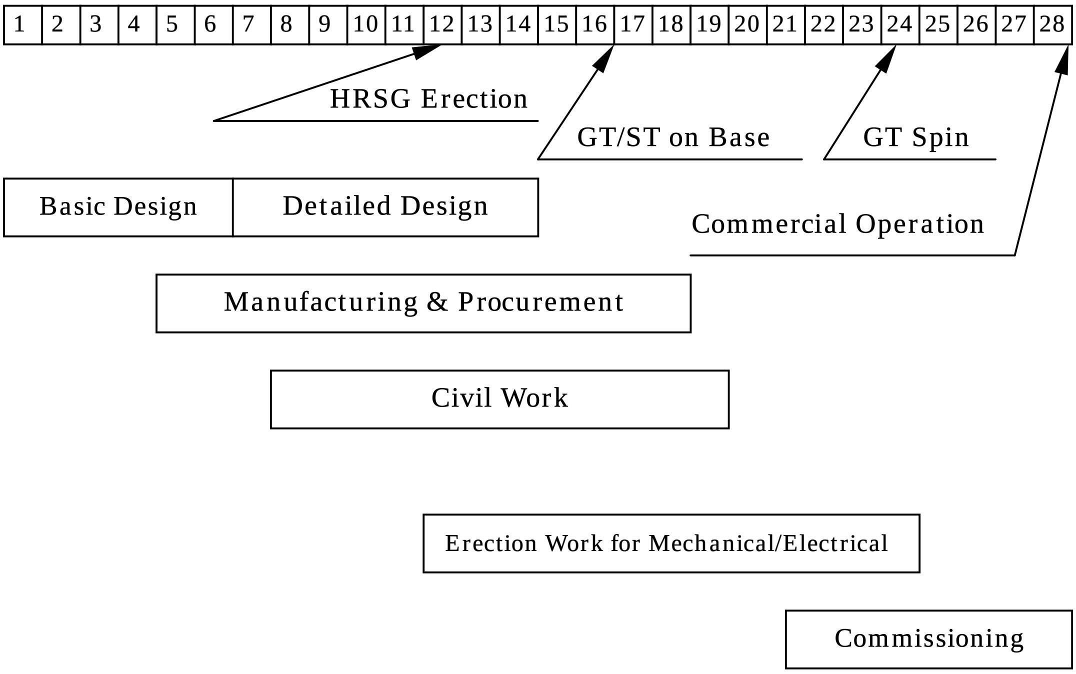


Figure 10　Typical Project Schedule for C/C Plant

Remote monitoring and maintenance supporting system

MHI can serve the operation and maintenance services after commercial operation. Remote monitoring and maintenance supporting system is one of MHI's maintenance services programs.
MHI has plant monitoring team in Takasago machinery Works that monitors the plants being contracted for 24 hours monitoring and advisory service in order to insure high availability and reliability operation as shown in Figure 11.
Since the real time operation index data are logged in Remote monitoring data base in Takasago through communication line or internet, Monitoring staff call the plant operator at jobsite about the incident detection, and quick advices after investigation by professional experts of MITSUBISHI are also available even in case of emergency

Of course, plant operator may consult with monitoring staff for operational recommendation and preventive maintenance planning during their duty.

Remote monitoring and maintenance supporting system have already been introduced to 15 units (8 plants), while in addition 12 units (4 plants) will come up soon in order to increase plant availability and reliability.

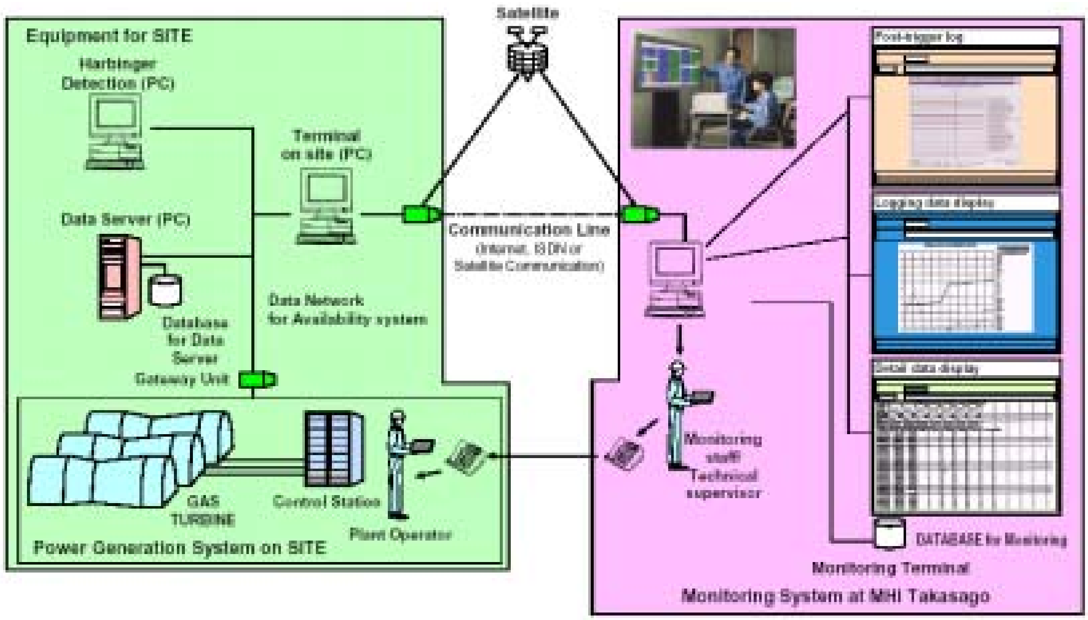


Figure 11　Remote Monitoring System

Conclusion

The Mitsubishi combined-cycle experience using F series gas turbine is extensive and worldwide, including 37,000MW of installed capacity with more than 1,200,000hours of gas turbine operation. The availability of total F series gas turbines has also achieved more than 98%. The Mitsubishi will continue to provide advanced combined-cycle plants worldwide especially in China with attractive economics, reliability, and operating flexibility incorporating customers' needs and requirements.