Development of 1500°C Class 501G Gas Turbine

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The next generation of large, heavy-duty, single-shaft gas turbines, 501 G, with a turbine inlet temperature in the 1500°C range has been developed by Mitsubishi Heavy Industries, Ltd. (MHI) Many advanced component technologies (a high efficiency compressor, a steam cooled combustor, a high temperature turbines, etc,) are employed in this turbine and achieve an excellent combined cycle performance. Various component tests have been conducted over the past 3 years. From February, 1997, a trial operation of the 501 G for 60 Hz utilities was performed at the verification test combined cycle plant at MHI, Takasago Machinery Works in Japan to verify its high performance, reliability and maintainability. Also, during the trial operation at this plant, more than 1800 instrumentation systems were installed in the engine. The flow path characteristics, metal temperatures, pressures, strains, sound pressure levels, exhaust emissions, etc. were measured over the full range of operating conditions. All important characteristics, including the cooling characteristics, and components reliability were verified.

1. Introduction

In the field of thermal power generation, the increasing attention has been focused on superiority of the overall thermal efficiency of the combined cycle plant system achieved by utilizing the steam produced with recovered heat from the gas turbine exhaust gas as the driving power of the turbine.

Remarkable improvement of the overall efficiency of the combined cycle plant can be expected with the application of a higher temperature and a higher performance of the gas turbine, the main engine of the system.

MHI developed the 1150°C class large-capacity gas turbine MW701D in 1981 and subsequently verified its high overall thermal efficiency, high reliability, and low air pollution at a natural-gas-utility combined cycle plant at Tohoku Electric Power Co., Inc. Higashi-Niigata Thermal Power Plant. In 1985, MHI started the development of a 1350°C class 501F/701F gas turbine in an effort to achieve a higher inlet temperature in the gas turbine. Up to 43 units of the 501F/701F gas turbine have already been ordered and been operating as the main engines of combined cycle plants both inside and outside Japan. These engines in operation, integrating high-level cooling technologies are displaying an excellent performance accumulating satisfactory operation experience.

Furthermore, based on MHI's abundant experience in gas turbine development, MHI started the development of a G-type gas turbine with a turbine inlet temperature of 1500°C (501G/701G) in 1993 to meet the social need for further improvement of the overall thermal efficiency of thermal power plants. A test run of the 501G gas turbine for the 60 Hz market was started in February 1997 at the Takasago in-house power station at MHI Takasago Machinery Works to verify the long-term reliability. A full-load running condition was achieved in success in April 1997.

The 501G gas turbine, whose longitudinal section is shown in **Fig. 1**, has the same basic mechanical construction as the 501F/701F gas turbine, which has been now accumulating satisfactory running experience, and the state-of-the-art components and technologies for the compressor, the combustor, and the turbine have been separately verified by various component tests.

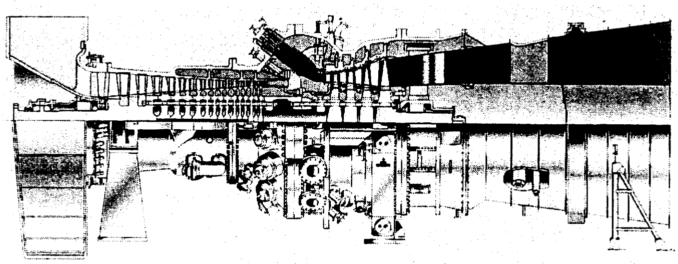

Fig. 1 Longitudinal section of 501 G gas turbine
Longitudinal cross section of the turbine-inlet-temperature-1500°C-class high-temperature 501 G gas turbine test run from February 1997 at the in-house verification test power station at the MHI Takasago Machinery Works.

Table 1 Performance of 501 G gas turbine

Item		501 G	501 F
Turbine inlet temp.	(℃)	1 500	1 350
Output	(MW)	230	159
Thermal efficiency	(%)	38.5	36
Press. ratio		19	15

In the development of the 501G gas turbine, various component tests were conducted at the basic design phase to acquire the design data, and their results were reflected in the detail design. The natural frequency of each blade of the compressor and turbine was confirmed in the high speed rotating vibration test by using an actual rotor.

In addition, in the test run at the Takasago in-house power station, the integration of as many as 1800 special instrumentation component devices was installed in the gas turbine in order to verify the long-term reliability. Their effective use enabled to verify the gas turbine performance, the cooling characteristics, and the reliability, based on the measured operation data on fluid pressure, temperature, flow rate, metal temperature, vibration stress, noise, property of the exhaust gas, and other characteristics.

2. Features of the 501G gas turbine

The 501G gas turbine is a high-performance gas turbine with a turbine inlet temperature of 1500°C and the target performance exceeds that of the 501F[(1)]. As shown in **Table 1**, 501G gas turbine is now running in success at Takasago in house power station.

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2. 1 Overall structure

The basic structure of the 501 G gas turbine is modeled after the 501 F/701 F gas turbine, which is designed based on the proven technologies which have been applied to the previous MHI's gas turbines. The following good features of the structure have been verified in our operation experience:

(1) For the rotor, the two-bearing support is applied, with the support from both the compressor-side bearing and turbine-side bearing.

(2) For the connection with the power generator shaft, a compressor shaft-end drive system is adopted so that any flexible coupling or something such that is not required because the thermal effect is so little.

(3) An axial flow exhaust configuration is adopted because it is optimum for the layout of a combined cycle generator plant.

(4) An external cooler and external filter are applied for the rotor cooling air system to reduce the metal temperature of the blades and prevent dust clogging.

(5) Regarding the bearing support structure, the compressor-side bearing is supported with eight radial struts, and the turbine-side bearing is supported by tangential struts which makes it easy to absorb the difference of thermal expansion while maintaining the shaft at the center.

(6) The structure of the turbine casing is split into two parts horizontally to make it easy to conduct the inspections.

(7) For connecting structure, discs with spigots are connected with bolts on the compressor-rotor side while discs with curvic couplings are connected with bolts on the turbine-rotor side.

2. 2 Design of compressor

In order to achieve a larger airflow, higher pressure ratio and higher efficiency, a new 17-stage axial flow type compressor adopting an MCA (Multiple Circular Arc) airfoil and CDA (Controlled Diffusion Airfoil) was newly designed for the 501 G gas turbine. The aerodynamic performance of these new airfoils was verified with the cascade test and model compressor test. The aerodynamic performance was also verified in the MF 221 gas turbine, whose compressor is half scale of that of the 501 G.

The cooling air is bled at 6th stage, 11th stage, and 14th stage, respectively. The inlet guide vane is a variable vane designed to improve the partial load performance of the combined cycle.

2. 3 Design of combustor

Fig. 2 shows the steam-cooled combustor. Because it is necessary to increase the air for combustion in order to achieve a NOx level approximately equal to that of the 501 F/701 F with the premixed type for the 1 500°C class gas turbine, the cooling air flow rate for the premix combustion is limited.[2] For this reason, MHI has decided to adopt the closed-type steam cooling system for the first time. The performance and reliability of this system have already been verified by both the atmospheric-pressure combustion test and high-pressure combustion test. It was confirmed that the NOx emission was less than 25 ppm in the value converted into actual gas turbine condition, which is almost equal to the level of the 501 F/701 F.

2. 4 Design of the turbine

The high-performance axial-flow type with four stages and heavy load was designed for the load increase caused by the turbine inlet temperature increase. A fully three-dimensional airfoil designed by stacking airfoil profiles along a curve in the radial direction is adopted to reduce the generation of the secondary loss near the airfoil surface.

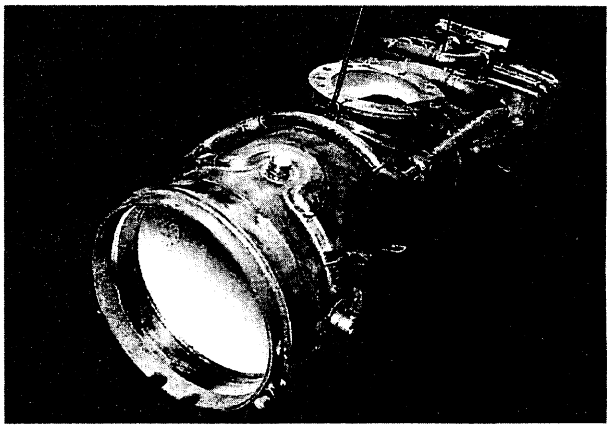

Fig. 2 Steam cooled combustor of 501 G gas turbine
New combustor adopting a closed-type steam cooling system in order to achieve the low NOx under the condition of a turbine inlet temperature of 1 500°C.

The cooling vanes and blades are adopted for the blades and vanes from the first to the third stages. In order to achieve the turbine inlet temperature of 1 500°C, the state-of-the-art cooling technologies (full coverage film cooling, shaped film cooling and angled turbulator, etc.), a thermal barrier coating (TBC), etc., are adopted to ensure that the metal temperature is kept at the level of the existing-type gas turbines.

The material for the vanes is a Ni-base alloy (MGA 2400) which has been newly developed by MHI and Mitsubishi Steel Mfg. Co., Ltd. (MSM) to improve the weldability. The first-stage vanes are single segments, while the second- through fourth-stage vanes are segmented vanes. The blades are made of a Ni-base alloy (MGA 1400) newly developed by MHI and

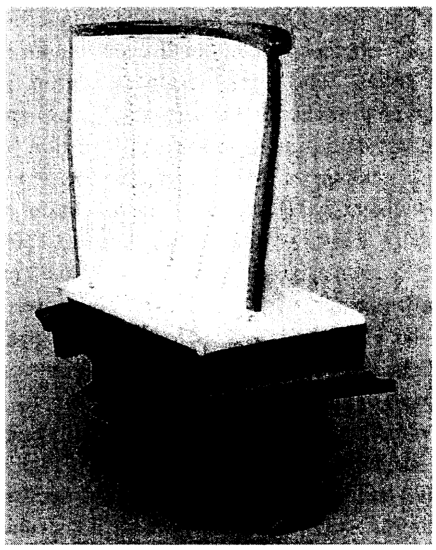

Fig. 3 First-stage turbine blade of 501 G gas turbine
First-stage turbine blade of 501 G gas turbine adopting full-coverage film cooling (shaped film hole), full-coverage TBC, directionally solidified material, and other state-of-the-art technologies.

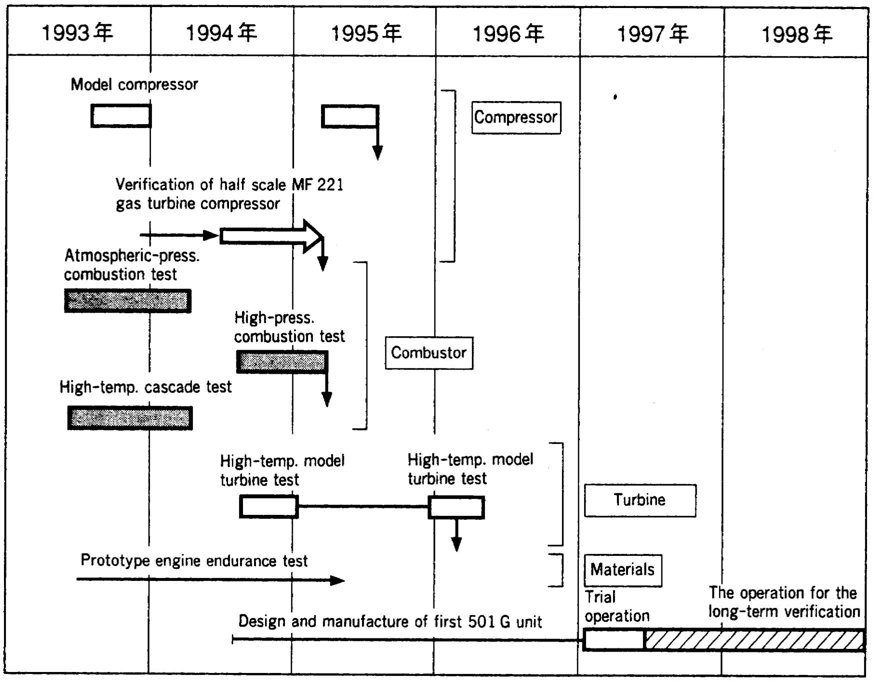

Fig. 4 Schedule of component verification test and manufacturing of 501 G gas turbine
The verification test for new technologies to be applied to the 501 G was carried out, the test results were incorporated into the detail design, and the first 501 G unit was then manufactured.

MSM to obtain a creep rapture life superior to that of the existing material applied to the F-type gas turbine. **Fig. 3** shows a first-stage turbine blade. The first and second stage blades are free standing blades, while the third and fourth stage blades adopt the same type of the integral "Z" tip shroud as that adopted in the F-type gas turbine in order to improve the vibration strength of the airfoils by increasing the structural damping.

2.5 Cooling air system

Turbine blades and vanes are cooled by the bleed air from the mid-stages of the compressor. The stage number from which cooling air is bled is determined in consideration of reducing the loss effecting on the gas turbine performance as much as possible. The first-stage vanes are cooled with the compressor discharge air while the second- through fourth-stage vanes are cooled by the bleed air from the 14th and 11th stage of the compressor, respectively. The bleed air from the sixth stage of the compressor is fed to the fourth-stage vane to cool the cavity area at the lower part of the vanes. Compressor discharge air cooled with an external cooler is used to cool the blade and rotor.

3. Verification test

3.1 Component verification test

The various component tests for the newly developed components and technologies applied to the compressor, combustor, and turbine of the 501 G gas turbine were conducted at the basic design phase, and their results were reflected to the detail design after their characteristics and reliabilities had been confirmed.

Fig. 4 shows the schedule of the verification test.

(1) Compressor model test

As described above, the 501 G gas turbine adopts a high-performance compressor designed to achieve a larger air flow capacity, higher pressure ratio, and higher efficiency than the current F-type compressor. In order to achieve a higher Mach number and higher efficiency operation, state-of-the-art MCA and CDA airfoils are adopted.

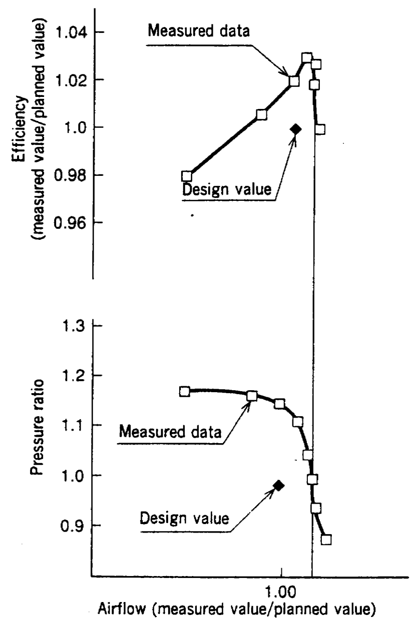

Fig. 5 Results of model compressor test for 501 G
A performance verification test of the 501 G using a model compressor with 0.28-scale 501 G blades and vanes was carried out, and both the obtained airflow and efficiency were confirmed to exceed their design values.

A model compressor integrating model 501 G blades and vanes at 0.28 scale was tested at the basic design phase to verify its performance.

Fig. 5 shows the test results of the model compressor test. It was confirmed that both the air flow and efficiency are better than the design values.

(2) Combustor test

In order to achieve the NOx level of 25 ppm with the premixed type under the condition of a turbine inlet temperature of 1 500°C, all of the air supplied to the combustor has to be used for the combustion. For this reason, MHI has developed a steam-cooled combustor, investigated its performance in the high-pressure combustion test, and incorporated the test results in its final design and verification of its final geometry. Finally, a high-pressure-combustion test was carried out using the actual combustor and the NOx of less than 25 ppm was confirmed under the condition of a turbine inlet temperature of 1 500°C.

(3) Cooled turbine blades and vanes

In order to achieve the turbine inlet temperature of 1 500°C, the state-of-the-art technologies for cooling such as full-coverage film cooling (shaped film holes) and angled turbulator, and full-coverage TBC are applied to the first-stage blades and vanes.[3]

The high cooling characteristics of the first-stage turbine blades and vanes have been confirmed and verified with the high-temperature cascade test using the actual blades and vanes, and the high-temperature rotating model turbine test (HTDU: High Temperature Demonstration Unit) with the 0.6 scaled model blades and vanes.

(4) Development of the new super alloys

To increase the creep strength of the turbine blades and vanes in conformance with the increase of the turbine inlet temperature up to 1 500°C, MHI manufactured the turbine vanes of MGA 2400, the new super alloy based on IN 939 Ni-base alloy, but with improved weldability.[2]

MGA 1400, the new super alloy developed by MHI to obtain a better creep strength, was adopted for the blade. Furthermore, directionally solidified material with a higher creep strength was applied to the first and second blades.

Fig. 6 shows a comparison of the creep strength data between the new materials and the current ones.

The creep strength value converted into metal temperature is 30°C better than that of the popularly used IN 738 LC material. In the first- and second-stage blades, the adoption of directionally solidified material has resulted in an additional improvement of 20°C in the creep strength value converted into metal temperature.

3.2 Rotating vibration test

In order to grasp the vibration characteristics of the compressor and turbine blades in advance, a rotating vibration

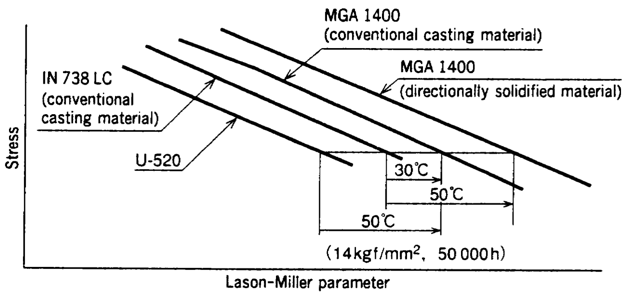

Fig. 6 Creep strength of material for turbine blades
MGA 1400, a heat-resistant alloy newly developed by MHI which has better creep strength than the other current materials.

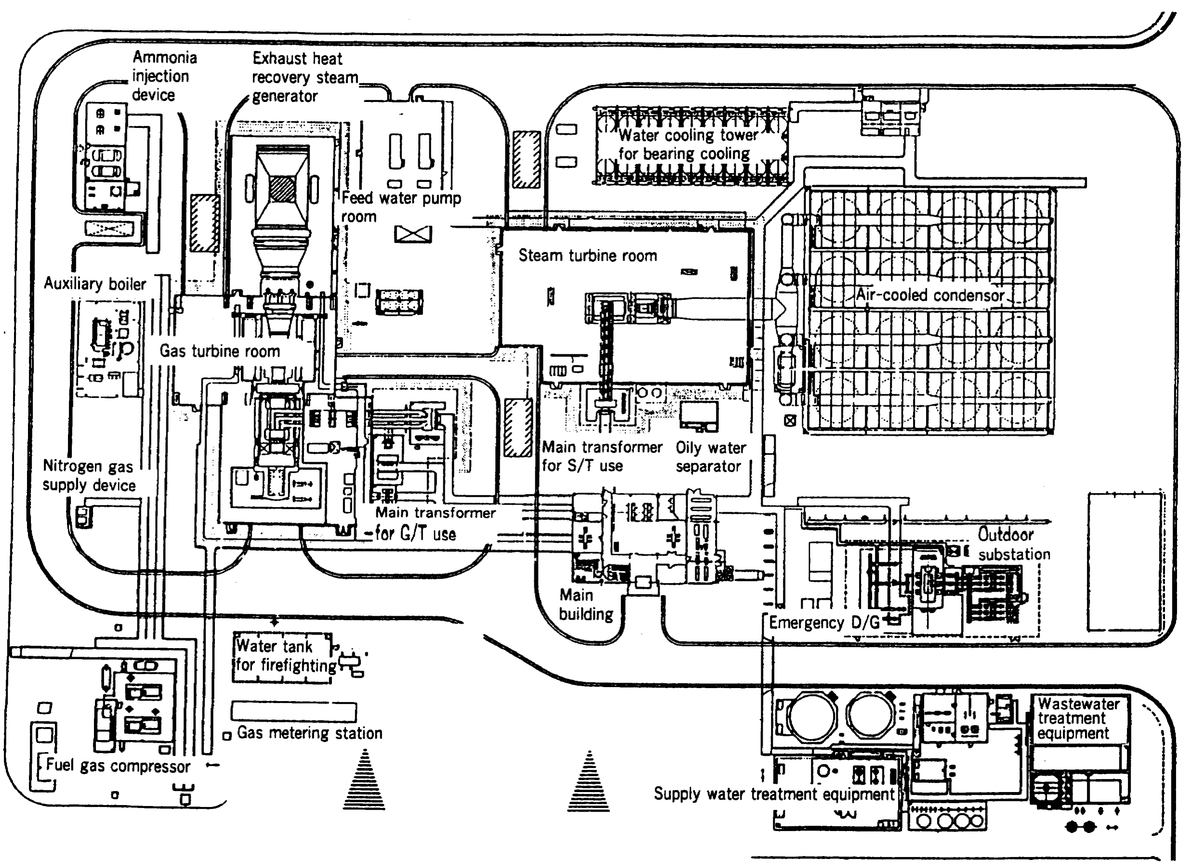

Fig. 7 Plant layout of combined cycle verification test plant at MHI Takasago Machinery Works
Layout of combined cycle verification test plant which has been in test run operation since February 1997.

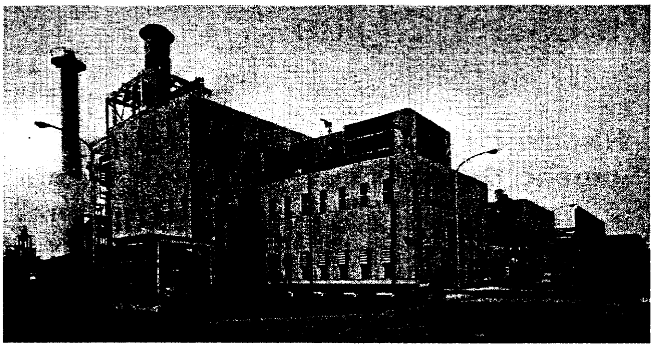

Fig. 8 Complete view of combined cycle verification test plant at MHI Takasago Machinery Works
Complete view of combined cycle verification test plant which has been in operation since February 1997.

test was carried out. Natural frequency and vibration damping characteristics were measured on the first-, second-, third-, fourth- and seventh-stage compressor blades and the first through fourth turbine blades, respectively. The rotors were accelerated up to 110% of the rating speed by an electric motor and measured using a high-vacuum, high-speed balancing machine. The measurement for the compressor blades frequency was carried out with a non-contact measurement system using an optical fiber. The vibration stress of the turbine blades was measured with strain gages on each blade and transmitted as a signal from the rotating article by using the telemetry system.

From our analysis of these data, the adequacy of the vibration characteristics and the damping effect of the shroud of the third- and fourth-stage turbine blades were verified.

4. Test on Takasago in-house power station for verification of long-term reliability

The 501 G gas turbine was installed on Takasago in-house power station newly constructed at the MHI Takasago Machinery Works for the verification of the long-term reliability. The trial operation was started in February targeting commencement of operation in June, 1997. This type power station, which is the first type in the world, is a multishaft-type combined cycle plant verification test facility with a capability of 225 000 kW gas turbine output and 105 000 kW steam turbine output, totaling 330 000 kW. **Fig. 7** shows its layout and **Fig. 8** shows its complete view.

A thyristor starting system is prepared to start up the plant and the gas turbine is accelerated using the generator as a synchronous motor. The cooling airflow for the rotors and second- through fourth-stage turbine vanes is measured with the orifice located at the inside of the external piping. A highly functional operation-monitoring system equipped with a fully digitalized control device, touch-operation function, alarm overlooking function, trend function, and multiwindow function is prepared in the control room. In addition, the temperature, the pressure, and the vibration stress at various points were monitored at all times during the trial operation of the 501 G gas turbine (**Table 2**). More than 1 800 component devices for the special measurement instrumentation were prepared for this purpose.

Table 2 List of special measurement items at test run of 501 G gas turbine

	Measurement item
Performance	Intake airflow Intake air temp. and press. Exhaust gas temp. and press. Fuel flow Generator output Compressor component performance Turbine component performance
Metal temp.	Combustor Turbine first- through fourth-stage blades Turbine first- through fourth-stage vanes Bearings Casing Blade rings Exhaust diffuser
Press./vibration	Compressor blades Compressor vanes Combustor Turbine blades Rotor shaft vibration Casing vibration Rotor torsional vibration
Others	Cooling airflow, press. and temp. Thrust force Exhaust gas emission Thermal expansion of rotor and casing Noise Lube oil temp.

5. Conclusion

We hope to obtain remarkable improvement of the overall thermal efficiency of the combined cycle plant for thermal electric power generation by increasing the applicable turbine inlet temperature and improving the efficiency of the gas turbine. MHI has developed a turbine inlet temperature 1 500°C class high-temperature/high-efficiency gas turbine 501 G. After commencing the trial operation for the first manufactured unit in February 1997, the full-load operation was achieved in April, and the trial operation for the verification of its performance and reliability was completed. We conducted the analysis of the special measurements during this trial operation, and the mechanical reliability and performance of this engine are very good.

After completion of this trial operation, the 501 G is scheduled to conduct a long-term operation. Many features on performance and reliability are expected to be clarified and verified through this long-term operation, and the 501 G gas turbine to be established thereafter is expected to contribute to society as a main facility for highly efficient combined cycle plants.

References

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