ABSTRACT

The 701F is a high temperature 50Hz industrial grade 220 MW size engine based on a scaling of the 501F 150MW class 60Hz machine, and incorporates a higher compressor pressure ratio to increase the thermal efficiency. The prototype engine is under a two-year performance and reliability verification testing program at MHI's Yokohama Plant and was initially fired in June of 1992. This paper describes the 701F design features design changes made from 501F. The associated performance and reliability verification test program will also be presented.

INTRODUCTION

The 701F is a 3000 RPM heavy-duty combustion turbine designed with a 1.2 scaling factor from the 150MW, 60Hz 501F to serve the 50Hz power generation needs for utility and industrial service. This engine, jointly developed by Mitsubishi Heavy Industries, Ltd., Westinghouse Electric Corporation, and Fiat Avio S.p.A., represents the latest in an evolutionary cycle that continues a long line of large single shaft heavy-duty combustion turbines. The 701F combines the efficient, reliable design concepts of the 501F with recently developed low emission combustion technology. The result is an advanced design, high temperature, efficient, low NOx, more powerful combustion turbine based on time proven reliable design concepts that will satisfy the large combustion turbine power generation needs for the next decade. Currently being targeted for 1992-1994 performance and durability test, it will have an initial simple cycle ISO rating of 221MW with a heat rate of 9,440 Btu/kWh (9,958 KJ/kWh) based on LHV at a turbine inlet temperature of 1260°C (1533K) on natural gas fuel. In combined cycle applications the heat rate will be better than 6,360 Btu/kWh (6,709 KJ/kWh) based on LHV with a single shaft application.

Across the board advances in computer technology have enabled manufacturers to improve analytical procedures in all aspects of design including stress analysis, heat transfer, aerodynamics, fluid mechanics, and structural dynamics. Benefits of these technological advances are shown in Figure 1, where optimal cooling system design allows metal temperature in the 701F to be kept within the MW501D/MW701D experience and have been verified in the 501F prototype engine shop test with extensive instrumentation installed in the engine. The first heavy-duty combustion turbine to incorporate advanced cooling technologies was the MF111 with initial commercial operation in August, 1986 at a turbine inlet temperature of 1160°C (1433K).

Figure 1 701F Metal and Gas Temperatures

For some critical components such as combustor baskets, transition pieces, and turbine row 1 and 2 blades and vanes, the 701F engine utilizes the components of the same size or the same basic dimensions as those of the 501F in order to enhance reliability and performance. This design philosophy enables this engine to benefit from the comprehensive 501F testing program which consisted of air cascades, turbine model tests, full-scale verification of combustor design, and rotor blade vibratory dynamics. The component testing was followed by an instrumented shop test at load and finally by an instrumented field test, which included tests of several design enhancements. In addition, stringent emission regulations in Japan provided increased incentive to develop the dry low NOx Hybrid Combustion system that has operated successfully at Tohoku Electric Power Company Higashi-Niigata Plant since 1984.
ENGINE DESIGN FEATURES

Figure 2 illustrates the general configuration of the 701F heavy-duty combustion turbine. Several basic long established design concepts and philosophies are evident and are presented below. Those features unique to the 701F are listed separately.

Figure 2 501F Longitudinal Section

General Description
- Two-bearing single shaft construction.
- Cold end generator drive to minimize the influence of thermal expansion and to eliminate the need for a flexible coupling.
- Axial flow exhaust system, which has a plant arrangement advantage in combined cycle power plants in meeting the heat recovery requirements.
- Externally cooled and filtered rotor and blade cooling air to eliminate excessive contaminants that could block critically intricate cooling passages of the rotor and blades.
- Tangential exhaust casing struts to maintain bearing housing alignment by rotating as required to accommodate thermal expansion.
- Variable inlet guide vane (IGV) to provide exhaust temperature control for heat recovery applications and to improve starting characteristics.
- Compressor diaphragms and dovetail root blades removable with the rotor in place.
- Three (3) axisymmetric compressor bleeds for turbine cooling with two (2) used to avoid surge during starting.
- Horizontally split casings to facilitate field maintenance with the rotor in place.
- Combustors and transitions removable without lifting cylinder covers.
- Stage 1 vanes removable without lifting cylinder cover.
- Turbine rotor with bolted CURVIC coupled discs providing precise alignment and torque carrying features.
- Fir-tree rooted turbine blades removable on-site with rotor in place.
- Multiple turbine blade ring concept to provide field service of vanes with the rotor in place and a thermal response independent of the outer casing to prevent blades rubs, minimize clearance, and maximize performance.
- Turbine ring segments and isolating ring structure to minimize the thermal distortion of the blade rings which support the turbine vanes.

701F Additional Features
- High temperature and efficient engine designed based on the proven 501F engine with the scale ratio of 1.2 with the exception of the combustors and turbine row 1 and 2 blade and vane airfoils which are identical to those of the 501F.
- Advanced hybrid combustion system incorporating low NOx features, consisting of 20 canular combustors with the same diameter and length as the 501F. The hybrid combustor features a two-stage burner assembly and a bypass valve which directs a portion of the compressor delivery air directly into the transition piece to enhance flame stability during starting and to maintain desired fuel/air ratio during loading. The 701F hybrid system differs from the current one by having the ratio of pilot to main fuel trimmed to reduce pilot burner NOx generation.
- Twin layer composite structure named "PLATEFIN" and "MTFIN" to provide more efficient cooling on the combustor basket and transition pieces respectively, thus providing more air for the low NOx system.
- Four (4) stage turbine to maintain low aerodynamic loading even at the increased firing temperature.
- Cooled stage 1 and 2 vane segment and cooled stage 1 and 2 blades with the basic same dimensions as 501F engine to utilize the 501F component/shop test results and field experiences. The first two stages of vanes and blades are protected by anti-oxidation coating. The first stage vane shrouds are also protected by thermal barrier coating. The Row 1 vane cooling design utilizes state-of-the-art concepts with three impingement inserts in combination with an array of film cooling exits and a trailing edge pin fin system. The first stage blade is cooled by a combination of convection techniques via multi-pass serpentine passages, pin fin cooling in the trailing edge exit slots, and film cooling including shower head scheme.
- Cooled stage 3 vane segment and turbine blade to improve reliability.
- Integral “Z” tip shrouds in third and fourth stage rotor blades for increased structural damping to minimize the potential for flow induced non-synchronous vibration.
- Damping and sealing pins in the first and second stage rotor blades to increase structural damping and minimize the leakage of cooling flow.
- Leading Edge Groove (LEG) direct lubricated thrust bearing to reduce the required oil flow and its mechanical loss.
- Two-element tilting pad journal bearings for load carrying and a fixed upper half bearing to eliminate top pad fluttering concerns and related local babbitt spragging.
- Compressor blade locking feature that is visibly inspectable.
- Improved compressor rotor blade root design that has flat contact faces for ease of manufacturing and inspection.
- Blade rings in compressor section to optimize cylinder to rotor alignment.
- Compressor design with multiple axial tie boles which eliminates the shrinkfitted design and main coupling joint to increase rotor dynamic stability margin as well as facilitate fabrication and maintenance of the rotor. Individual disks are positioned radially by bore rabbit joints.
- 17 stage, highly efficient axial flow compressor with pressure ratio of 16:1, incorporating larger diameter rear stages to help balance spindle thrust and two exit guide vanes to straighthen the flow leaving the compressor.
- Turbine flow path design utilizing fully three-dimensional flow analysis.

COMPONENT VERIFICATION

For some critical components, the 701F engine utilizes components of the same size or same basic dimensions as the 501F. This design philosophy enables the engine to benefit from the comprehensive 501F test program and operating experience. As an integral part of the 701F engine development program, performance and durability testing including rotating blade vibration tests, a two-year performance and durability test program for performance measurement in various ambient conditions, and durability and emissions verifications in long-term daily start/stop operation. In the test at MHI's newly constructed power station operating on natural gas in Yokohama, the generator was coupled with the 701F engine in the same manner as in the simple cycle unit with the downstream high temperature SCR (selective catalytic removal) system as shown in Figure 3. The generated electrical output is delivered to 50Hz utility grid. About 1300 special measurement
points were applied to the engine during the integrated testing program.

Figure 3 701F Gas Turbine Plant in Yokohama

Rotating Blade Vibration Test

A rotating blade vibration test was performed to verify the vibration characteristics of selected rotating compressor and turbine blades. The first and second stage compressor blades and all four turbine stage blades were tested to verify natural frequencies. Damping characteristics were also measured for the turbine 1st and 2nd stage blades with seal pins and also the 3rd and 4th stage shrouded blades of the turbine. These damping characteristics will be used to obtain turbine blade dynamic response via a cyclic symmetry computer routine.

During the test, performed in a vacuum room, the fully bladed rotor was driven by an electric motor up to 110% of rated speed. The frequencies and amplitude of compressor blade vibration were measured using a non-contact optical fiber monitoring system. This system measures the movement of each individual blade tip by monitoring the position of each blade tip from several different locations circumferentially and analyzing this information through a synchronizing process. The schematic of this measuring system is shown in Figure 4. In the turbine, strain gauges were applied directly to the blades of each stage and the measured strain signals were transmitted to a data acquisition system through a telemetry system. After analyzing all measured data, it was confirmed that no further tuning was necessary for the blades.

Engine Verification Test

In order to verify the performance and design characteristics of the 701F, a two-year test program for performance, durability and emissions was started in June, 1992. Figure 5 presents an overall general arrangement of the Mitsubishi Power Station, showing the major components: gas turbine, generator, exciter, control and...
special instrumentation room, cooling air cooler, gas compressor, SCR, and intake and exhaust stacks.

About 1,300 special measurement points were applied to the engine for the verification of the following:

- Individual compressor and turbine performance as well as overall gas turbine performance. Parameters included air flow, power output, heat rate and exhaust temperature.
- Compressor inlet air flow over the entire IGV range. The compressor air supply duct system employed a bell-mouth inlet to measure air flow precisely.
- Engine starting and acceleration characteristics including light-off, rotor vibration, and rotating stall.
- Mechanical operation of the engine from starting to overspeed including rotor vibration characteristics.
- Mechanical and thermal performance of the engine over its entire operating range.
- Reliability of the engine by measurement of gas and metal temperature, pressure, vibratory stresses, etc. The hot parts' metal temperatures will be confirmed to be below allowables at the associated 1260°C (1533K) rotor inlet temperature. Monitored components include combustor basket, transitions, turbine vanes, blades, and turbine ring segment. Vibratory stresses of the compressor and turbine blades, bearing temperatures, casing temperature, and disc cavity temperatures are monitored continuously during the test. In addition, axial and radial growths are monitored at strategic locations in the engine to verify design calculations.
- Emission characteristics of the engine. Emissions testing includes sampling for nitrogen oxides (NOx), nitric oxide (NO), volatile organic compounds (VOC), carbon monoxide (CO), unburned hydrocarbons (UHC), carbon dioxide (CO2), and oxygen (O2).

Monitoring System during Engine Operation

In addition to the supervisory instrumentation, the engine is extensively instrumented to measure thermodynamic performance parameters, metal temperatures, static and vibratory strains, vibration characteristics, displacements, and other parameters as shown in Figure 6. Dynamic strain gauges will be installed on the turbine blades to verify dynamic responses. The signals from the rotating sensing are transmitted by a telemetry system. Clearance measurement system using proximity probes allow stator to rotor radial and axial displacement measurements during transients. Through the use of an infrared pyrometer, it will be possible to obtain the temperature distribution on each turbine blade of the first stage under operating conditions. Data acquisition equipment is installed to record the special engineering test data. This equipment includes tape recorders, spectrum analyzers, plotters and chart recorders.

Data critical to the continued operation of the engine, such as metal temperatures of hot parts and cavity temperatures, are monitored on computer displays together with associated alarm limits. Turbine inlet temperature of the operating engine can be calculated from measured data using a heat balance calculation program.

TEST RESULTS

The 701F performance and durability testing is a two-year program which started in June, 1992. Summarized below are the test results measured at the initial stage of this program.

Starting and Acceleration

This plant is started by operating the generator as a motor via a static frequency converter. The starting schedule includes a 5-minute exhaust stack purge, ignition at 550-600rpm, disengagement of the static frequency converter at 2000rpm, an IGV position change at 2100rpm and bleed valve closure at 2755rpm. The elapsed time from pushing starting button to synchronizing speed is under 18 minutes and time to full load is under 37 minutes as shown in Figure 7. At ignition speed, two combustors located at the bottom of the engine are ignited and cross-flame tubes produce complete ignition. Compressor rotating stall was cleared at less than 1700rpm. Throughout the starting sequence, compressor operating characteristics were stable.

Overall Performance

Measured performance data were analyzed and corrected from shop test conditions to standard ambient conditions. The results show that the measured power output and inlet air flow exceeded the predicted values. In addition, the heat rate is slightly better than the predicted value. Since performance will be measured
for the various ambient conditions during the two-year test program, new performance ratings will be established after completion of the test program.

Figure 7 Starting Characteristics

Emission
Nitrogen oxides (NOx), carbon monoxide (CO), unburned hydrocarbons (UHC), volatile organic compound (VOC), and other emissions were measured. Since premixed type combustors are used, the setting schedules of inlet guide vanes and bypass valves affect the combustion performance. Figure 8 shows the dynamic pressure fluctuation measured inside the combustor. Stable combustion was assured throughout engine start up and load operation. Low NOx emission level was measured not only at full load condition, but also at lower load conditions including idle condition. At rated load (150MW) of this plant, measured emission levels were by far lower than the target level of 50ppm at dry conditions.

Hot Parts Temperature
Figure 9 presents metal temperatures measured along the span of a row 1 vane leading edge. The temperatures were obtained from thermocouples which were mounted on the surface of the vane airfoils. Figure 10 presents the combustor system metal temperatures. It was confirmed that the measured hot parts temperatures were within the acceptable range and this also verified expected temperature at design conditions. Evaluation of hot parts data is continuing and more detailed turbine blade and vane temperatures will be verified in the next stage in the test program.

Table 1 Performance Results

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<th>EXPECTED</th>
<th>MEASURED</th>
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<tr>
<td>POWER, NET KW</td>
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Figure 8 Combustor Pressure Fluctuation

Vibratory Stresses
Figure 11 presents vibratory stresses as measured during the test along with corresponding design allowables on the Goodman diagram. Frequency and damping factors were also verified during the test. Vibratory stresses of other stationary components such as a combustor transition, tangential strut shield cover, exhaust diffuser support, etc., were measured. As shown in Figure 12, all measured stresses were within the design allowables.

Figure 13 summarizes rotor dynamic responses during start up. Vibration levels were low during acceleration to running speed and the associated phase angles during rated speed operation were virtually constant.
Cooling Flow Circuit

The measurement results established the correlations between the various engine cavity temperatures and the supervisory instrumentation installed in all engines to assure that specific temperature limits are never exceeded during normal operation. The individual cooling circuit flows were measured via orifice plates installed in the external piping while important engine cavity temperatures were monitored simultaneously with supervisory and special test thermocouples.

FUTURE TEST PLAN

The two-year test program of the first 701F engine started at the beginning of June, 1992. Initially, the engine was operated in an introductory rating mode, i.e., the rotor inlet temperature was reduced. This is the only prudent way to introduce a reliable engine to the market which features a step change in firing temperature technology. Mechanical technologies necessary to achieve significant increase in turbine firing temperature should be verified via operating experience prior to operation at the rated rotor inlet temperature of 1260°C (1533K). This will result in a more reliable product when operated at rated conditions.

SUMMARY

The 701F prototype engine performance and durability testing has been continuing successfully since June, 1992. Overall performance is better than anticipated and NOx emission levels are far below the target. The operation of the generator as a motor via a static frequency converter was verified to be adequate during the starting and acceleration testing. Mechanical characteristics such as vibratory stresses of blades and diaphragms, thrust force, axial/radial clearances, and bearing and turbine blade and vane metal temperatures were confirmed to be within the design limits. The two-year test program includes more detailed data measurements at various operating conditions. Recently developed low NOx combustor and other associated design enhancements will also be verified in this program.

REFERENCES