Development of Ceramic Components for a Power Generating Gas Turbine

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ABSTRACT

Since 1984, TEPCO (Tokyo Electric Power Co., Inc.) has been conducting a cooperative research program to apply ceramics to power generating gas turbines with three Japanese gas turbine manufacturers (Toshiba Corporation, Mitsubishi Heavy Industries, Ltd., and Hitachi, Ltd.). The goal of the program is development of a 20MW class gas turbine with turbine inlet temperature of 1,300°C (1,573K) to improve the efficiency of coal gasification combined cycle power generation.

Preliminary design of the gas turbine was conducted during 1984-1985 and basic design criteria, such as desired configuration and material properties, were established. Based on the results of the preliminary design, it was decided to apply ceramics to the liner and transition piece of the combustor, the 1st and 2nd stage nozzles and 1st stage rotor in a three stage turbine. As for the rotors, development efforts were also applied to thermal barrier coatings on conventional metal blades.

Parallel efforts have been conducted on the development of each ceramic component since 1986. This paper will review the design of ceramic components from structural and material standpoints, and present results obtained from tests conducted under various operational conditions.

1. INTRODUCTION

Considering the future energy situation, there is a strong expectation that the coal gasification combined cycle power plant will be an effective method for the utilization of a large amount of coal. In order to achieve economically acceptable efficiency of the plant, it is necessary to develop a highly efficient gas turbine which can be operated at turbine inlet temperatures higher than the present level.

Since the introduction of the gas turbine, there has been a continuing demand for improvements in performance. Over the last 45 years, the turbine inlet temperature has increased from 800°C (1,472K) to 1,300°C (1,573K). These improvements have been made mainly by the introduction of nickel based superalloys with sophisticated turbine cooling techniques. Future requirements for increases in turbine inlet temperature can be met either by introducing improved superalloys such as directionally solidified superalloys, single crystals and oxide-dispersion-strengthened superalloys along with advanced turbine cooling techniques or by the utilization of ceramic components without using cooling air. Since there is an increasing penalty in efficiency by providing progressively larger amounts of cooling air to maintain the surface temperature of metallic components below their usable temperature, there is a strong drive towards the introduction of ceramic components into gas turbines.

Ceramics, especially the silicon based non-oxide ceramics such as silicon carbide and silicon nitride, offer a very attractive combination of high temperature capability to about 1,300°C (1,573K) - 1,400°C (1,673K), high stiffness and high strength. This leads to an increase in the usable turbine temperature and the reduction of cooling air, which in turn lead to improved thermal efficiency. Ceramics also offer advantages in terms of wear resistance and erosion/corrosion behavior.

These advantages sparked a great deal of interest in the early 1970's and a large amount of work has been done in the U.S.A. and Europe since then, especially in the application of ceramics to automobile gas turbine engines and land-based gas turbines. However, despite considerable efforts on various ceramic engine programs, there has been only limited success in the use of ceramics for structural components in the hot section of gas turbines. Although ceramic materials have superior high temperature properties to nickel based superalloys, the unpredictable behaviour due to their brittleness has prevented widespread introduction of ceramics into critical areas of the gas turbine.

In Japan, two national R and D projects are...
presently being carried out to explore small size (100~300KW) ceramic gas turbines. One is for automobile engines and the other is for cogeneration services. For large power generating gas turbines, there are two groups in Japan presently conducting research projects related to the application of ceramics to hot parts of gas turbines. One is led by the Central Research Institute of Electric Power Industry (CRIEPI) and the other is the joint research program of Tokyo Electric Power Company (TEPCO) and three Japanese gas turbine manufacturers.

Since 1984, TEPCO has been conducting a cooperative research program for the application of ceramics to power generating gas turbines with Hitachi, Ltd., Mitsubishi Heavy Industries, Ltd. and Toshiba Corporation [1] ~ [3]. The goal of the program is development of a prototype ceramic gas turbine to improve the efficiency of coal gasification combined cycle power generation. This paper will review the design of ceramic components for a generating gas turbine from structural and material standpoints, and will present the results obtained from tests conducted under various operational conditions.

2. OBJECTIVES AND SCHEDULES

The goal of the program is the development of a prototype ceramic gas turbine with output power and turbine inlet temperature set at 20MW and 1,300°C(1,573K). Ceramics will be applied to the components which are exposed to hot combustion gas, such as the liner and transition piece of the combustor, the first and second stage nozzle vanes, and first stage rotor blade in the three-stage turbine.

Figure 1 shows the development schedule of the present program. The program consists of the following three phases:

Phase 1: Fundamental Research (1984-1985)
Phase 2: Application Research (1985-1992)

In phase 1 of the program, preliminary design of a ceramic gas turbine was conducted and basic design criteria, such as the desired configuration and required material properties, were established for the ceramic components.

Based on the results obtained in the preliminary design, phase 2 efforts have been initiated for the development of ceramic components such as combustor, nozzle vanes, and rotor blades. The development of these components consists of the following three steps:

Step 1: Design, stress analysis, and tests under atmospheric conditions.
Step 2: Modification of design based on the results and findings obtained in step 1, and tests under full-pressure conditions. (An exception is rotor blades, which were evaluated by room-temperature spin tests).
Step 3: Further development of ceramic rotor blades. Hot spin tests will be performed to evaluate the validity of design.

Research has also been carried out in phase 2 toward the development of a reliability analysis system, and property evaluation for the candidate ceramic materials. Tests have been carried out under various operational conditions to confirm the practical applicability of ceramics to power generating gas turbines. The design has been reviewed repeatedly from the structural and material standpoints in phase 2.

Development is presently at the final stage of phase 2, which is the development of ceramic components, as shown in Figure 1. Given success in the component development, it is intended to transfer the various techniques and lessons obtained in this phase to phase 3, in which a 20MW gas turbine using ceramic combustor, ceramic nozzle vanes, and thermal barrier coated rotor blades will be constructed and tests will be conducted to evaluate performance and reliability. In the case of the ceramic rotor blades, the component development effort will be continued as step 3 of phase 2. Ceramic rotor blades will replace the thermal barrier coated blades later on after the reliability of the ceramic rotor is confirmed.

3. PRELIMINARY DESIGN

Preliminary design of the gas turbine was conducted during the 1984-1985 period, and basic design criteria were established. Based on the results of this preliminary design, it was decided to apply ceramics to the liner and transition piece of combustor, the 1st and 2nd stage nozzles and 1st stage rotor in the 3-stage turbine as shown in Figure 2. There is potential for the widespread use of ceramic components in the hot section of a gas turbine. The final choice of component will depend on a combination of factors including design payback, probability of success, difficulty of manufacture and effect of failure on downstream components. As for the rotor blade, parallel efforts have been directed at both thermal barrier coating on the conventional superalloy systems and all-ceramic rotor blades.

Table 1 presents the specifications for the gas turbine which is under development. The power output of 20MW was selected as the target of the program because this class seems to be the most suitable size to scale up the developed techniques to a practical power generation system (100 ~150MW class) in the future. Figure 3 shows the heat balance at the design point.

4. SELECTION OF CERAMIC MATERIALS

In recent years a wide variety of silicon-based ceramics have emerged with potential as structural components in gas turbines. Silicon nitride (Si3N4) and silicon carbide (SiC) are currently regarded as the most promising candidates for gas turbine application. The available materials represent a large family with wide property variations and different responses to the gas turbine environment.

Silicon carbide is one of the leading candidates for gas turbine application because of its high strength, good oxidation and wear resistance at elevated temperatures. SiC has also extremely good creep strength and microstructural stability and higher thermal conductivity than Si3N4. This means that SiC would be a good candidate for components which will be exposed to high temperature environments, greater than 1,300°C(1,573K) to 1,400°C(1,673K). Therefore SiC ceramics were considered as the most promising material for components such as the combustor, first stage
nozzles and first stage rotors. The major disadvantages of SiC when directly compared with Si3N4 are its lower fracture toughness and lower thermal shock resistance. The low toughness of SiC is due to its low critical stress intensity factor and low fracture surface energy. The low thermal shock resistance of SiC is due to the combination of its higher thermal expansion and higher elastic modulus in comparison with Si3N4.

Si3N4 ceramics have the excellent strength, toughness and thermal shock resistance at temperature below 1,200°C (1,473K) to 1,300°C (1,573K), although they tend to degrade at temperatures above 1,300°C (1,573K). However, high performance Si3N4 ceramics have been developed recently which demonstrate little degradation of strength and excellent oxidation resistance up to around 1,400°C (1,673K). Although corrosion resistance in the combustion gas environment and the long term reliability at high temperature are not yet clarified, the reliability of ceramic components is expected to improve if Si3N4 can be adopted for first stage nozzles and first stage rotors instead of SiC. It also appears that advances in Si3N4 technology are being made much more rapidly than advances in SiC technology. Therefore, both SiC and Si3N4 are considered presently as candidate materials for these components.

These materials range from commercially available to highly developmental. Even though some are termed commercially available, they are in a continual state of development and change. Thus, the intended application and the processing maturity must be considered in selecting materials. In order to select appropriate materials, material evaluation tests have been carried out for many ceramics that are commercial and underdevelopment. Tests were conducted at room temperature to establish a baseline, and at the appropriate elevated temperature ranges where the properties are expected to begin to change rapidly.

Table 2 summarizes the predicted operational conditions for each component. In case of the last stage nozzle and 1st stage rotor, thermal and centrifugal stresses seem to be very critical in considering strength of candidate materials. On the other hand, it seems to be less critical to apply ceramics for the combustor and 2nd stage nozzles because the stress levels are rather low compared with the strength of the candidate materials.

5. DEVELOPMENT OF CERAMIC COMPONENTS

Following the preliminary design, a development program on ceramic components has been performed and significant progress has been made toward the practical application of ceramic components to industrial gas turbines. For this development, parallel programs were initiated and design, fabrication and performance evaluation have been conducted through extensive laboratory testing at both atmospheric and full pressure conditions for each component. Also, development of a thermal barrier coating on a metal rotor blade has been conducted. Table 3 presents the design conditions for the turbine.

Development of Ceramic Combustor

Development of the combustor has been conducted in a cooperative research program between TEPCO and Toshiba Corporation.

Table 1 Specifications of the Ceramic Gas Turbine

<table>
<thead>
<tr>
<th>Output</th>
<th>20MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbine Inlet Temp.</td>
<td>1300°C</td>
</tr>
<tr>
<td>Exhaust Gas Temp.</td>
<td>666°C</td>
</tr>
<tr>
<td>Pressure Ratio</td>
<td>15</td>
</tr>
<tr>
<td>Shaft Speed</td>
<td>10800rpm</td>
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</tbody>
</table>
Preliminary design and tests. In the 1st step of the ceramic combustor development, two combustor concepts were designed and tested [4]. One was a ring type and another was a tile type. The inner diameter was 200mm and the overall length was about 550mm. The ring type combustor was composed of six ceramic rings which were made of SiC and inserted into an outer metal casing. The tile type combustor was composed of about 50 pieces of SiC ceramic tiles which were mechanically supported in the metal case. These ceramic rings and tiles were supported by soft insulation materials. Atmospheric pressure combustion tests with low calorific value gas fuel simulating coal derived gas were performed for both types of combustors. Excellent combustion performance and reliability of SiC rings and tiles were confirmed.

Structural design. Based on results obtained in the preliminary design stage, the final structure of the combustor was determined as shown in Figure 4. The combustor liner is composed of 6 stages of ceramic rings with 5mm thickness. These ceramic rings and tiles are supported by soft insulation materials which are placed in the space between the ceramic rings and metal outer casing. The insulation material, made of Al2O3 and SiO2, serves as protection for the metal case as well as support of the ceramics. Ceramic tiles have been adopted to reduce the thermal stresses for the portion around the air intake holes where the temperature gradient is expected to be most steep. As for the transition piece, the ceramics are divided into four pieces to avoid generation of excess thermal stress.

Ceramic materials. Material requirements for the combustor are high thermal shock resistance and high corrosion resistance. Because SiC ceramics have greater hot-corrosion and oxidation resistance than Si3N4, it was decided to use SiC ceramics for the combustor. Pressureless sintered SiC was selected for both ceramic rings and ceramic tiles.

Stress analysis. Mechanical stresses are likely to be low, consisting mainly of combustion gas pressure and attachment stresses. Reliability of ceramic combustors may be impaired by the possibility of local thermal stress concentration caused by hot spots. An analysis of thermal stresses on the ceramics was conducted. Methods for relaxing thermal stresses on the ceramic wall were investigated and a guideline was established for designing ceramic combustors with walls that are divided into rings.

Combustion tests. In order to develop a ceramic combustor for use in a coal gasification combined power generation system, combustion tests were conducted in a research facility that can produce simulated low-BTU coal gas [5]. There are three specific features in coal derived gaseous fuel produced by the air blown entrained bed coal gasifier:
(a) The calorific value is very low (App. 1,000Kcal/Nm3).
(b) Carbon monoxide is a major component of the combustible gas, and
(c) Ammonia is present if the gas clean up system is of the hot dry type.

Full pressure combustion tests were performed with a simulated coal gas having a calorific value of...
930Kcal/Nm³ to evaluate combustion performance and ceramic material reliability. It was found that a highly satisfactory combustion efficiency was obtained over a broad range of load conditions, as shown in Figure 5, with a pressure loss of about 3% and a temperature nonuniformity (i.e., pattern factor) of about 10% at the rated load condition. Highly satisfactory NOx exhaust characteristics were obtained for fuel NOx as well as thermal NOx emission. The thermal NOx emission characteristics are presented in Figure 6. Figure 7 presents the temperature distribution along the combustor. In addition to good combustion characteristics, it was also confirmed that the ceramic parts were healthy and sound after the trip test, in which fuel was cut instantaneously at full-load condition. The test results have confirmed that the ceramic combustor has a high potential for practical application to gas turbines.

Development of Ceramic Nozzles

Development of nozzles has been conducted in a cooperative research program between TEPCO and Mitsubishi Heavy Industry, Ltd.

The major requirements for this component are thermal shock resistance, thermal cycling resistance, oxidation, corrosion, erosion resistance and impact resistance.

Structural design. In the preliminary design and stress analysis, it was predicted that high thermal stress would be generated if a one-piece solid ceramic construction was adopted for the nozzle and shroud configurations. Therefore, the ceramic vane assembly was divided into three parts, i.e. airfoil, inner shroud and outer shroud to avoid excessive thermal stresses generated by uneven temperature distribution [6]. A hybrid construction was adopted with metal shrouds and a metal core along with these ceramic parts. Figure 8 shows the assembly construction of the ceramic first stage nozzle. The ceramic airfoil and the inner and outer ceramic shrouds were tightened and fixed from both sides with the metal shrouds and the metal core. Buffer materials were inserted between these metal and ceramic shrouds to make the tightening loads uniform and to insulate heat transfer between them. In addition, to reduce the thermal expansion differences between these metal and ceramic parts, a metal core of low thermal expansion Ni-base alloy was used. To limit thermal expansion of the metal core, cooling holes were provided at its middle section for effective internal cooling. Thermal insulation material was inserted between the metal core and the ceramic airfoil. Furthermore, a thermal barrier coating was applied to the outer surface of the metal core. To facilitate manufacture of the three-dimensional configurations of the vanes, the difference between each adjacent airfoil cross-section was minimized resulting in a vane configuration with little twisting. In addition, for the leading edge of the airfoil where the heat flux tends to be quite high, a blunt nose configuration was adopted to keep its heat transfer coefficient as low as possible.

Ceramic materials. In selecting the ceramic materials for the nozzles, the radial temperature distributions were taken into consideration by assuming that the pattern factor of the combustor is 0.10 at an average gas temperature of 1.300°C (1573K). Then the maximum gas temperatures
at the inlets of nozzles are about 1,400°C (1,673K) for the first stage and 1,100°C (1,373K) for the second stage. Accordingly, pressureless sintered SiC was used for the first stage nozzles and pressureless sintered Si3N4 for the second stage nozzles. Application of Si3N4 to the first stage nozzles was also investigated.

Stress analysis. Nozzle vanes experience thermal stresses due to uneven temperature distributions and mechanical stresses due to gas loading and contact stresses at attachment points. An FEM stress analysis was carried out for each of above-mentioned stresses and it was found that the most critical stress would be the transient thermal stress generated during emergency shutdown. Figure 9 shows the calculated thermal stress distribution generated in an airfoil at one second after emergency shutdown. The maximum tensile stress is about 370 MPa, which is generated at mid-span and at the suction side of the trailing edge. During shutdown transients, the central section remains relatively hotter and stiffer due to the volume effect, resulting in higher radial tensile stress fields around the total outer boundary of the airfoil except near the pressure side central section where the heat transfer coefficient tends to be low. These tensile stresses are maximized at the leading and trailing edges. Although the transient thermal stresses in the airfoil element of the vane were reduced to some degree by a reduction of the cross-sectional size of the airfoil, it is still quite high and further efforts are necessary to reduce the stress level. It was found that increasing the trailing edge thickness was effective with some loss of efficiency. It may be necessary to consider a trade-off between efficiency and reliability.

Cascade tests. Following the tests under atmospheric pressure conditions, a series of middle-pressure tests for the 1st stage nozzles were carried out at 3 ata and 6 ata pressure conditions before conducting tests under full-pressure (15 ata) conditions [7]. The full-pressure tests were carried out using a cascade of four ceramic nozzle assemblies with appropriately modified metal side vanes. The temperature pattern for the first stage nozzle cascade tests are presented in Figure 10. The tests were conducted in two steps, i.e. the steady state test with normal shutdown and trip test. The nozzles were disassembled and their component parts were inspected after a series of tests. Visual appearance and penetrant inspections were carried out carefully for each part. No cracks were found and the ceramic parts were healthy and sound. Similarly, cascade tests for the second stage nozzles were carried out under the actual operating conditions as well as over-load conditions. Thirty hours endurance tests were also conducted to confirm the soundness of ceramic parts.

Development of Ceramic Rotor

Unlike the stationary nozzle vanes, rotating rotor blades experience high mechanical and thermal stresses coupled with erosion and corrosion in a hostile environment. The demands on the rotor blades are consequently very high. They must be resistant to creep, thermal shock, erosion, corrosion/oxidation, cyclic fatigue, vibration and impact of foreign objects.

A review of the past work was instrumental in
establishing that stresses associated with attachment are most critical to successful application of brittle materials. Therefore, the efforts were focused on the most important and critical part, i.e. the blade attachment design. The approach consisted of an interactive procedure between design, stress analysis, material development, and static and rotational testing.

Development of the ceramic rotor and TBC blade has been conducted in a cooperative research program between TEPCO and Hitachi, Ltd.

Structural design. A three-component design has been adopted, which is consisting of a cooled disk, an intermediate metal piece or shank and ceramic blade. The metal shanks are connected to the disk by a conventional fir tree attachment. In turn, the ceramic rotor blades are attached to the metal shank by dovetail attachment. Each ceramic rotor has an integral airfoil, platform and dovetail root. Compliant pads have been incorporated into the design between the ceramic and metal contact surfaces in order to minimize the resulting local stresses [8]. Several design modifications were made on the dovetail root configuration to improve and control the geometric fit and to reduce the local contact stresses generated on the contact surfaces. The magnitude of the stresses induced by the centrifugal load and the differential thermal expansion varies as a function of the friction coefficient between the contacting surfaces. In order to minimize these stresses, the pads should serve as a lubricating layer as well as a compliant layer. The optimum characteristics that the metal pads should exhibit in order to accomplish these functions were investigated. Figure 11 shows the structure of the first stage ceramic rotor. Two metal pads of Ni-base or Co-base alloy are inserted symmetrically in the fitting layer to transfer the centrifugal force of the rotating blades to the metal shank, and a thermal insulator made of ceramic fiber is to be inserted into the rest of the space of the fitting layer to reduce heat transfer from blade to metal shank and disk.

Ceramic materials. Considering that the temperature of the 1st stage rotor reaches 1,250°C (1,523K) in relative total temperature, a pressureless sintered silicon carbide was initially considered as a primary candidate for the rotor blade material. However, a pressureless sintered silicon nitride is presently being considered for the rotor materials because work is progressing to improve the elevated-temperature properties of silicon nitride materials.

Stress analysis. The major problem to be solved in developing a ceramic rotor blade is the root attachment where high contact loads occur as induced by the centrifugal forces of rotation. Three dimensional analysis of the distribution of these stresses was conducted as a function of variable geometric design parameters, material parameters and temperature conditions of turbine operation. The root cross-sectional geometry was first optimized analytically by conducting a parametric two-dimensional finite element analysis. Having selected a preferred root design, it was analyzed in detail to determine the magnitude and location of stresses and temperatures. A three-dimensional finite-element stress analysis was carried out for the airfoil and dovetail root subjected to steady-
state thermal and centrifugal loading conditions. The magnitude and distribution of stresses in the ceramic blade are presented in Figure 12. The maximum tensile stress at the root of dovetail is about 290 MPa. These results point to the need for designs that would reduce the maximum tensile stresses in the root.

Testing. Since the attachment of the ceramic blade to the metal shank is a critical problem area in development of a ceramic rotor, testing of attachment methods is important. Tensile tests and room-temperature spin tests were performed in order to verify the strength of the ceramic rotor subjected to centrifugal force. At first, tensile tests in a static test rig were carried out at room temperature and at 600°C (873 K) utilizing specimens which had root forms at each end. Then, room-temperature spin tests have been performed on the specimens, made of SiC or Si3N4, having root forms selected and simplified two-dimensional straight airfoils. It was confirmed that the ceramic rotor blades were able to sustain centrifugal force up to 120% of the rated rotational speed. Some of the ceramic rotor blade specimens could survive 140% of the rated speed. A series of spin tests at room temperature have provided encouraging results and indicated the direction of further development.

Development of Thermal Barrier Coated Rotor Blade

Thermal barrier coatings (TBC) have been successfully used over the years in applications in stationary components such as combustors and turbine nozzle vanes. However, thermal barrier coatings on rotor blades have not commercially been used. The conditions that must be considered in developing a TBC for rotor blade application include high temperature oxidizing gases, thermal cycling, and centrifugal stress. The greatest concern involves thermally driven spalling of the ceramic coatings. The spalling of current coatings results from progressive accumulation of cracking damage in the ceramic adjacent to the ceramic-metal interface. Cracking is driven by cyclic thermal strains resulting from differences in thermal expansion between the ceramic and the underlying base metal. Cracking is augmented by metal oxidation at the metal-ceramic interface.

In order to cope with these problems, a four-layer thermal barrier coating has been developed [9]. Figure 13 shows a schematic sectional view of the developed coating. The innermost metallic layer, termed the bond coat, is plasma sprayed CoNiCrAlY and provides a rough surface for adherence. The metal-ceramic mixture layer reduces thermal stresses within the coatings and the outer metal layer is effective to prevent oxidation and corrosion of the mixture layer. The outermost ceramic layer, termed the top coat, is plasma sprayed Zirconia partially stabilized with 8 wt% Yttria.

Thermal cycle tests were conducted by burner heating and air cooling utilizing cylindrical specimens. It was confirmed that the life of the four-layer coating is about two times that of the conventional two-layer coating. Furthermore, cascade tests in a static test rig have been performed for the four-layer coated blades under the actual thermal and pressure conditions. The temperature of the base metal was measured with and without the coatings. The four-layer coating demonstrated about 90°C temperature reduction, which
is much superior to that of a conventional two layer coating. In addition to the tests for heat resistance, cycle tests of one hour holding at high temperature of 1,250°C(1,523K) followed by a trip were carried out 10 cycles to evaluate the endurance of the coating. No apparent damage was detected by inspection after the tests.

6. SUMMARY

The development of ceramic components for a power generating gas turbine has been reported. The target for the development was a 20MW prototype with turbine inlet temperature of 1,300°C(1,573K). Research has been conducted to apply ceramics to the liner and transition piece of the combustor, the 1st and 2nd stage nozzles and the 1st stage rotor in a three-stage turbine. For the rotor, parallel efforts have been conducted on thermal barrier coatings on conventional metal blades.

Combustion tests on the combustor and cascade tests on the nozzles have been conducted under full-pressure and full-temperature conditions and the applicability of ceramics has been verified for these stationary components.

Further efforts may be necessary for ceramic rotors to overcome the problems associated with rotating blades. In addition to centrifugal force, rotor blades are subjected to thermal stresses such as the steady-state stresses at normal operating condition and transient stresses at trip condition. Moreover, the problem associated with blade vibration must be overcome. To address these difficulties, it is intended to perform thermal loading tests by using a high temperature combustion gas environment and hot spin tests.

Meanwhile there is a strong possibility that a thermal barrier coated blade can be practically used for the rotor. The four-layer coated blade developed for this program has demonstrated excellent insulating effect and sufficient durability.

It is planned to verify the validity of the ceramic combustor, ceramic nozzle vanes, and ceramic coated rotor blade in a forthcoming assembly test of the 20MW prototype gas turbine. The TBC rotor blades will be replaced by all-ceramic rotor blades after the reliability of the ceramic rotor is confirmed.

REFERENCES