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DEVELOPMENT OF 300 kW CLASS CERAMIC GAS TURBINE (CGT302)

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ABSTRACT

With the aim of achieving higher efficiency, lower pollutant emissions, and multi-fuel capability for small to medium-sized gas turbine engines for use in co-generation systems, a ceramic gas turbine (CGT) research and development program is being promoted by the Japanese Ministry of International Trade and Industry (MITI) as a part of its "New Sunshine Project". Kawasaki Heavy Industries (KHI) is participating in this program and developing a regenerative two-shaft CGT (CGT302).

In 1993, KHI conducted the first test run of an engine with full ceramic components. At present, the CGT302 achieves 28.8% thermal efficiency at a turbine inlet temperature (TIT) of 1117°C under ISO standard conditions and an actual TIT of 1250°C has been confirmed at the rated speed of the basic CGT.

This paper consists of the current state of development of the CGT302 and how ceramic components are applied.

INTRODUCTION

To save energy and protect the environment, the Japanese Ministry of International Trade and Industry (MITI) is promoting a national program entitled the "New Sunshine Project". The research and development of a 300kW class CGT is one part of this project conducted by the New Energy and Industrial Technology Development Organization (NEDO).

Gas turbines have such advantages as high power, light weight, and low emissions, but the low thermal efficiency, especially in small and medium sized engines hinders their popularization. Fig. 1 shows the thermal efficiency of industrial gas turbines and the target for the CGT arranged by output power. Small gas turbines tend to have low efficiency because of limitations to turbine inlet temperature. In a small gas turbine, it is difficult to apply advanced internal component cooling systems because of the limitation in blade size. Using ceramic components, as in the CGT, eliminates the need for this advanced cooling system.

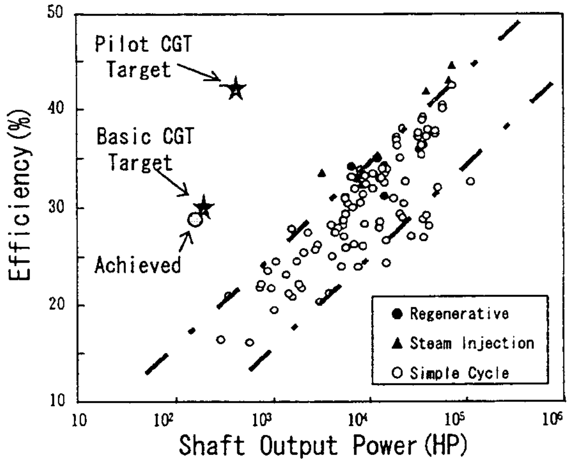

Fig. 1 Thermal efficiency of industrial gas turbines and the target for the CGT (1)

The CGT development program has three stages: 900°C Metal Gas Turbine (MGT), 1200°C (Basic) CGT and 1350°C (Pilot) CGT, as shown in Table 1.

There are three types of CGT in this project, one of which is the CGT302 developed by KHI in co-operation with Kyocera Corporation as the ceramic component supplier and Sumitomo

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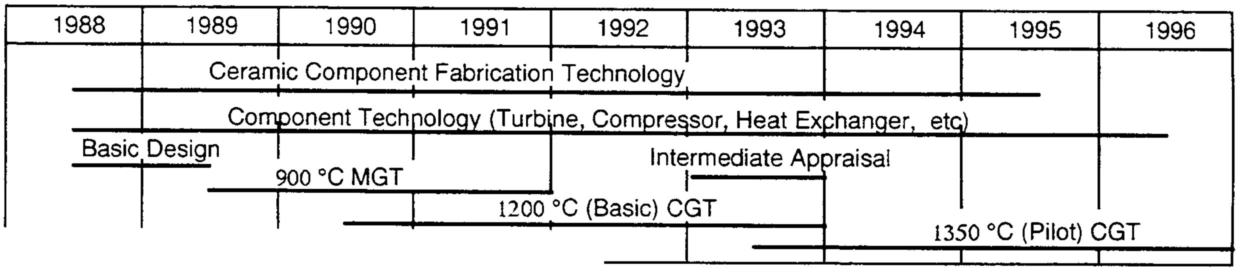
Table 1 The Progress of CGT Project



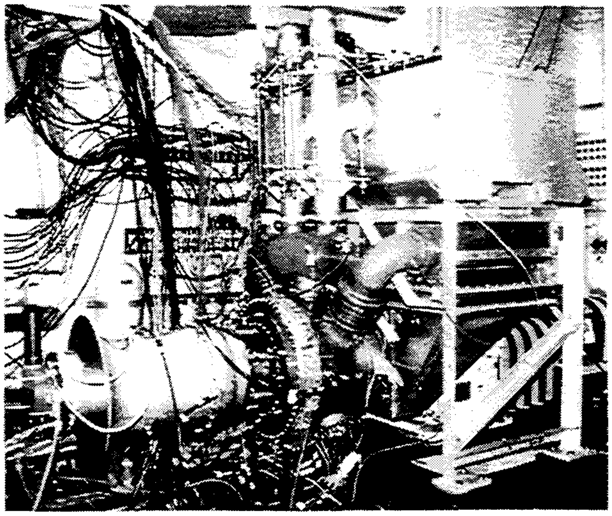


Fig. 2 The CGT302 engine

Precision Products Co., Ltd. (SPP) as the recuperator supplier. Fig. 2 shows the CGT302 engine and Fig. 3 shows its cross section. The power turbine of the CGT302 is a hybrid wheel inserted ceramic blade into a metal disc and the gas generator is an integrated ceramic wheel. The most remarkable feature of the CGT302 is a unique attachment technique applied to the segmental ceramic components. All the ceramic parts shown in Fig. 4 are made of silicon nitride "SN252" developed by Kyocera. The performance parameters target of the CGT302 is indicated in Table 2.

In this paper we describe this attachment technique and the current state of development of the CGT302. For more information on the CGT302, refer to 94-GT-19(2), 94-GT-482(3) and the rests(4)(5).

R&D OF TECHNOLOGY FOR FABRICATING HYBRID COMPONENTS

We studied the feasibility of forming a turbine scroll from segments, which is the largest of all the ceramic components, in order to simplify such manufacturing processes as forming and sintering, and to reduce thermal stress in service. In parallel, we also studied forming a complex shaped turbine nozzle from segments in order to reduce the thermal stress on the thin airfoil in service. The ceramic segments are bound together with ceramic fibers, which are subsequently converted into fiber-reinforced

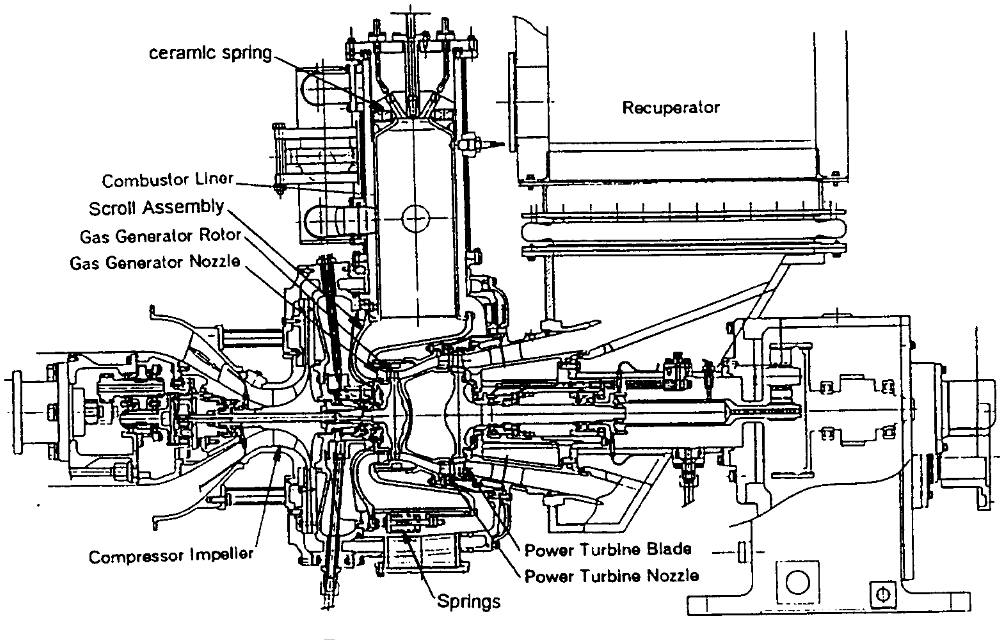


Fig.3 The cross section of the CGT302

Table 2 Target performance of the CGT302

Item	Unit	Final Target (Pilot CGT)	Target (Basic CGT)	Achieved Data (Basic CGT)	
Maximum Power	kW(PS)	300(408)	140(190)	130(176)	171(232)
Thermal Efficiency	%	42	30	28.8	26.6^{*1}
Turbine Inlet Temp.	°C	1,350	1,200	1,117	$1,209^{*2}$
Air Flow	kg/s	0.89	0.68	0.746	0.817
Pressure Ratio	-	8	5.9	5.07	5.89
GGT Speed	rpm	76,000	68,400	64,900	$68,400^{*2}$
PT Speed	rpm	57,000	51,300	39,700	39,500
Compressor Efficiency	%	82	78	76.2	76.2
Turbine Efficiency (GGT+PT)	%	85.5	82.2	83.5	82.5
Heat Exchanger Efficiency	%	80	78	80.7	66.7^{*1}

*1 ; not coming to thermal equilibrium

*2 ; Actual Data : 1250 °C / 69,200 rpm

ceramic (FRC), and finally a monolithic ceramic ring with high thermal resistance is at the inner high-temperature gas-path section and a fiber-reinforced ceramic with high fracture toughness is at the outer low-temperature section.

(1)Manufacturing and evaluation of composite component models

(a) Demand of binding strength. We carried out calculations of heat conduction and thermal stress in composite components, such as the turbine scroll and turbine nozzle, of the Pilot CGT in service. We found that the binding strength of the turbine scroll should be greater than 1 GPa of tensile strength at 1200℃.

(b) Fibers and matrix. We chose silicon-carbide fiber-reinforced silicon-carbide (SiC/SiC) which has suitable oxidation resistance and strength at 1200℃ for the binding material. Candidate fibers for binding were subjected to tensile tests after high temperature oxidation for 100 hours, and we singled out SiC fiber (Textron SCS-6) produced by chemical-vapor-deposition (CVD). Fig. 5 shows the tensile test results of the fibers. For synthesizing the ceramic matrix, the method of converting an organo-silicon polymer impregnated between the fibers was adopted.

(c) Manufacturing of composite component models. Ceramic segments, each a 90° quadrant of a cylindrical scroll, were formed from silicon nitride (SN252). The ceramic segments were bound with SiC fibers (Textron SCS-6) by the filament winding method. Then, organosilicon polymer was impregnated between the fibers or plies of the wound ceramic fiber and subsequently was converted to a ceramic matrix by heat treatment. We manufactured five types of cylindrical composite component models, in some of which the FRC was bound with fine SiC fiber (Nippon Carbon Nicalon) and treated with a SiC-CVD coating to prevent separation of the fibers. Fig. 6 shows the basic process for manufacturing composite components by binding segments. Fig. 7 is a schematic view of the composite component models.

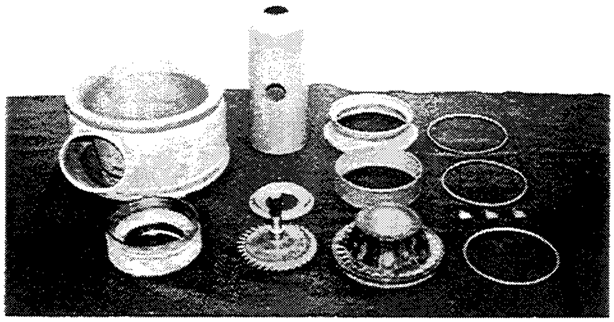


Fig.4 All ceramic components of the Basic CGT

(d) Evaluation of manufactured composite component models. We carried out thermal cycle tests at the actual service environment temperature of the Pilot CGT (approx. 1200℃) to evaluate the heat resistance of the manufactured products. Fig. 8 shows the test conditions, and Table 3 shows the results of the tests. After the thermal cycle tests, we tested binder strengths. The criteria of evaluation were that draw out strength should be greater than 98 N, the maximum estimated load, and that resisting pressure should be greater than 7.8 MPa, three times the design stress. Table 3 shows the results of the tests. Type 2, 3, and 4 bound with Nicalon to prevent separation of the fibers were damaged at the Nicalon layer in the thermal cycle test. Type 1 with the SiC-CVD coating to prevent separation of the fibers, was not damaged in the thermal cycle test and exhibited sufficient strength. Based on these

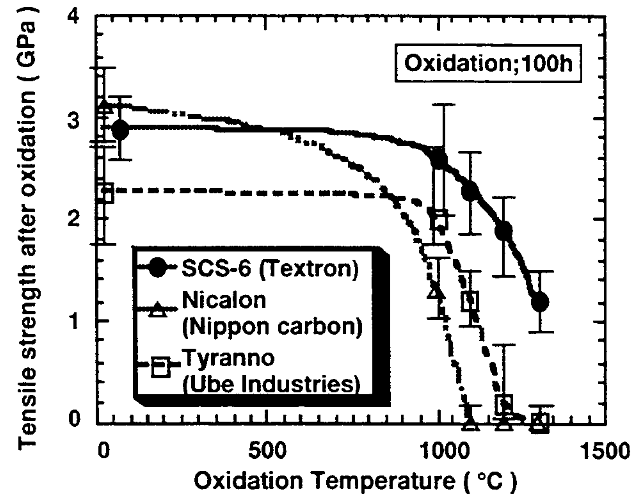


Fig. 5 Tensile strength of fibers after oxidation for 100 h

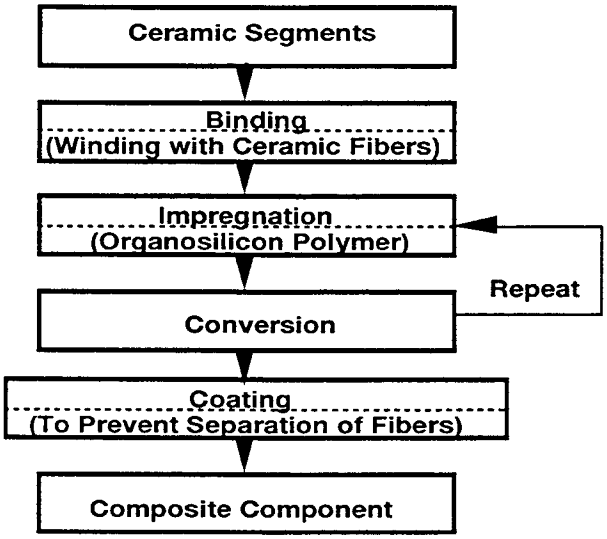


Fig. 6 Basic process for manufacturing

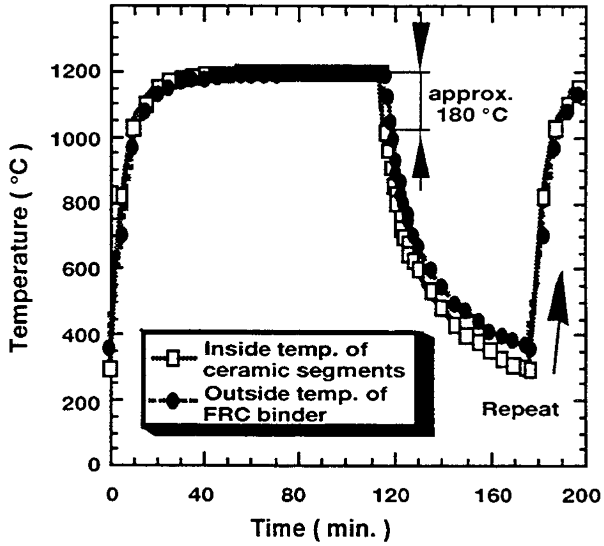


Fig. 8 Conditions of thermal cycle test

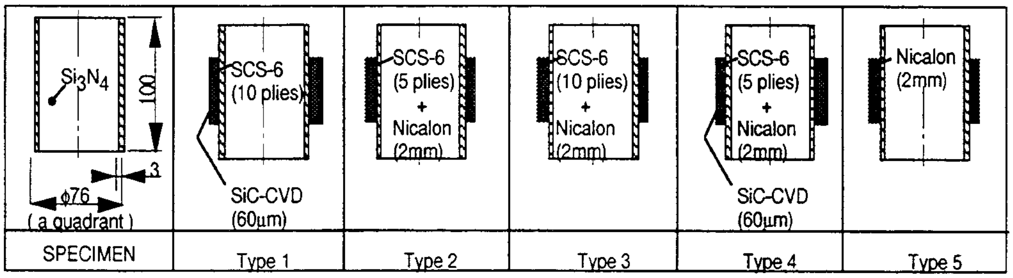


Fig. 7 Schematic view of composite component models

test results, we chose Type 1 as a binding structure of the actual composite components of the Basic CGT.

(2) Evaluation of application of the binding technique to actual composite components

Following the basic process (Fig. 6), we manufactured turbine scroll composite components with ceramic segments of silicon-nitride (SN252) by the method that had been evaluated to be most suitable. To evaluate the heat resistance of the manufactured product, we carried out thermal cycle tests at the actual service environment temperature (approx. 1200℃). The tests conditions were the same as those for the composite component models. Inspection after the tests revealed that the trial-manufactured product was not damaged and the binding fibers had not separated. Fig. 9 shows the trial-manufactured product after the thermal cycle tests. We trial-manufactured gas generator turbine (GGT) nozzle and power turbine (PT) nozzle composite components by the same method and got similar results. Based on these tests results, we concluded that the binding technique is applicable to manufacturing actual composite components of the Basic CGT.

(3) Improvement of the binding technique

We have begun a study of coating the binding part for manufacturing composite components of the Pilot CGT for the purpose of improving the oxidation resistance and high temperature strength of binding parts of composite components. We are studying SiC-CVD process parameters such as pressure, temperature and rate of carrier gas not only to prevent separation of binding fibers but also to improve the high temperature strength. In this study, we will examine the relation between CVD process parameters and the morphology of residual open porosities of binding parts.

R&D OF ENGINE COMPONENT

(1) Compressor

Five different blade types of compressor (A - E) and several types of diffuser (pipe/channel or different angle) were designed and tested in the engine or the rig. Fig. 10 shows the rig test results for the combination of type E impeller (front loading type) with PB-3 pipe diffuser and type E impeller with PB-1 pipe diffuser. The differences of PB-1 and PB-3 diffuser are shown in Table 4.

Table 3 Results of the evaluation of cylindrical composite component models

Type of model	Thermal cycle test		Binding strength test (98 N load)			Pressure test (216 MPa)	Remarks	Evaluation
	Conditions	Observation after test	R.T	1050 °C	1200 °C			
Type 1	1050 °C X 100 cycles, ΔT = 140 °C	•Separation of fibers not detected	No damage.	No damage.	Did not test yet.	No damage.	As expected, the SiC coating sealed the joints.	Excellent
	1200 °C X 100 cycles, ΔT = 160 °C	•Separation of fibers not detected.	No damage.	Did not test yet.	All right.	No damage.		Good
Type 2	1050 °C X 100 cycles, ΔT = 140 °C	•Some cracks occured at Nicalon layer (to prevent separation of fibers). •Separation of fibers not detected.	No damage.	No damage.	Did not test yet.	No damage.		Good
Type 3	1050 °C X 100 cycles, ΔT = 140 °C	•Some cracks occured at Nicalon layer (to prevent separation of fibers). •Separation of fibers not detected.	No damage.	No damage.	Did not test yet.	No damage.		Good
Type 4	1200 °C X 100 cycles, ΔT = 160 °C	•SiC-CVD layer was ruptured. •Nicalon layers (to prevent separation of fibers) were ruptured.	No damage.	Did not test yet.	Did not test yet.	No damage.		Good
Type 5	1050 °C X 100 cycles, ΔT = 140 °C	•Nicalon layers were ruptured.	Unable to test	Unable to test	Unable to test	Unable to test		Poor

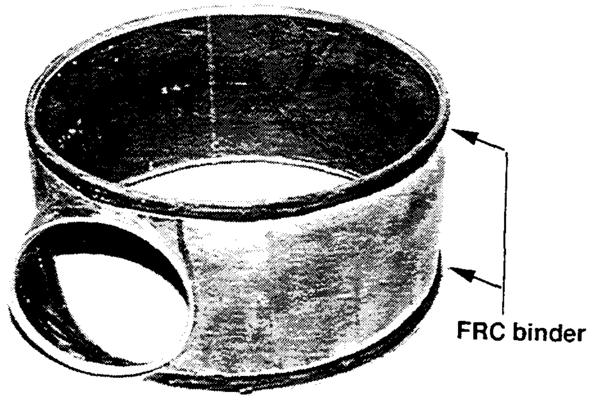


Fig. 9 Trial-manufactured turbine scroll comosite components after thermal cycle tests

As a result of these tests, it was confirmed that the throat area of PB-3 should be nearly equal to that of PB-1 to decrease the diffuser surge flow rate and the impeller throat area should be enlarged to increase the choke flow rate for the purpose of obtaining a wider operating range in the high speed area.

(2) Combustor

Fig. 11 is a schematic drawing of the combustor of the basic CGT. The ceramic liner is supported by ceramic coil springs . These springs absorb the difference in thermal expansion between the ceramic liner and the metal casings. The combustor is equipped with two bypass lines that each has one air bypass valve. The two valves are controlled to keep the air fuel ratio (A/F) in the combustion zone in a suitable range, although the total A/F ratio changes widely over a broad operating range.

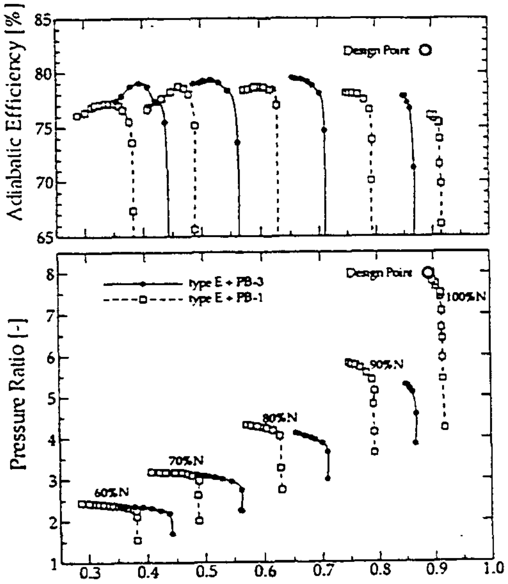


Fig. 10 The rig test results of compressor

Table 4 The differences of PB-1 and PB-3 diffuser

	PB-1	PB-3
Number of pipe	17	25
Throat area (mm^2)	751	908
Inlet vane angle (deg)	14.1	18.6

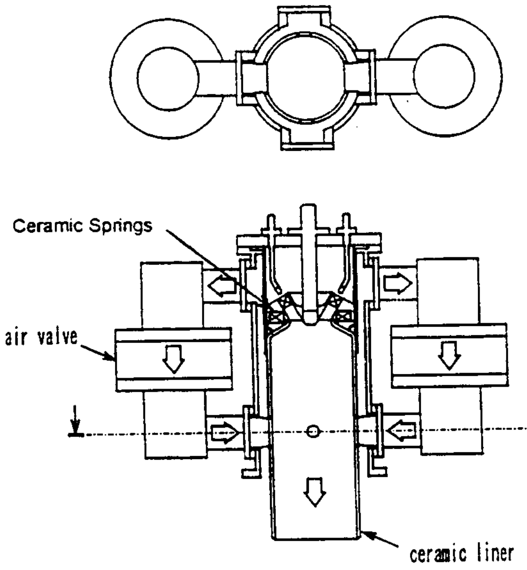


Fig. 11 Schematic drawing of combustor

Combustion rig tests including the rated conditions of the basic CGT were carried out. The results of these tests are shown in Fig. 12. In this figure, NOx emissions and combustion efficiencies are plotted as a function of A/F, with a parameter of air valves openings of bypass lines.

(3) Turbine

Several turbine component tests, i.e. thermal shock test (hot rig test) for stationary parts, cold and hot spin test for rotating parts, and performance test, have been carried out.

In order to evaluate the configuration of the ceramic stationary parts in the engine system, thermal shock tests contained 100 cycle test were carried out. After these tests for stationary parts, engine test installed full ceramic parts began.

Before starting the cycle test, the temperature variation mode was determined by a preliminary test, measuring the temperature of the outer scroll surface with an infrared thermo-viewer. The results are shown in Fig. 13. The 100 cycle test was carried out according to these results. Fig. 14 shows the recorded temperature chart. In this figure, nozzle inlet temperature can be seemed over 1200°C, this is the results that the test was carried out with some margin (approx. 50°C). After this test, no damage was detected in any ceramic part.

Turbine performance was measured in the actual engine. Turbine efficiency of the joined GGT and PT was 84%, greater than the 82.2% target value for the basic CGT. Fig. 15 shows turbine efficiency in the basic CGT engine.

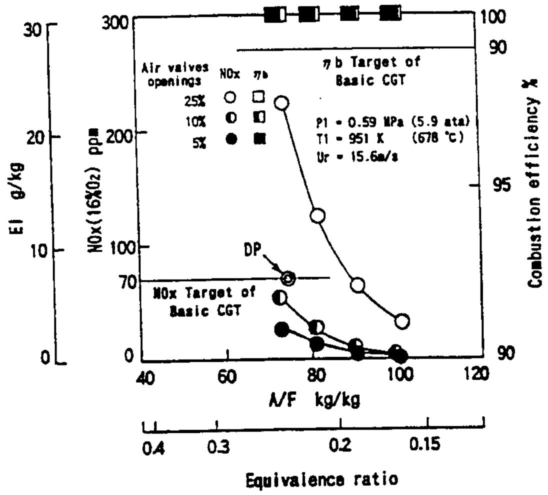


Fig. 12 Combustion efficiency and NOx emissions

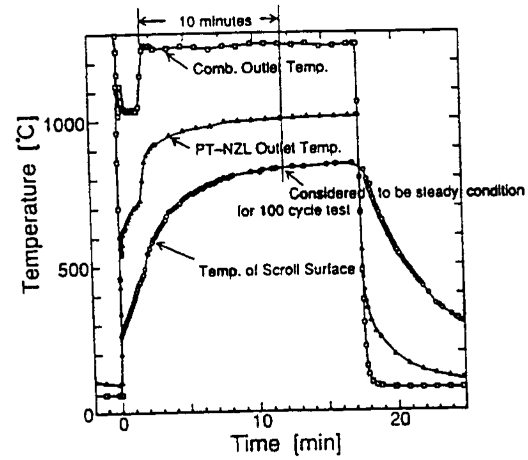


Fig. 13 Temperature of scroll surface

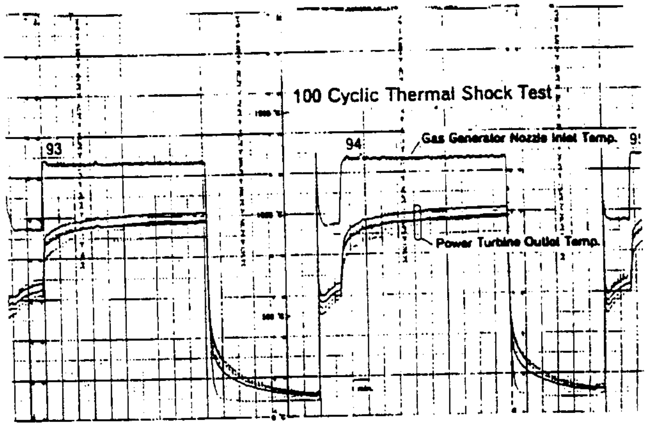


Fig. 14 The recorded temperature chart in the cycle test

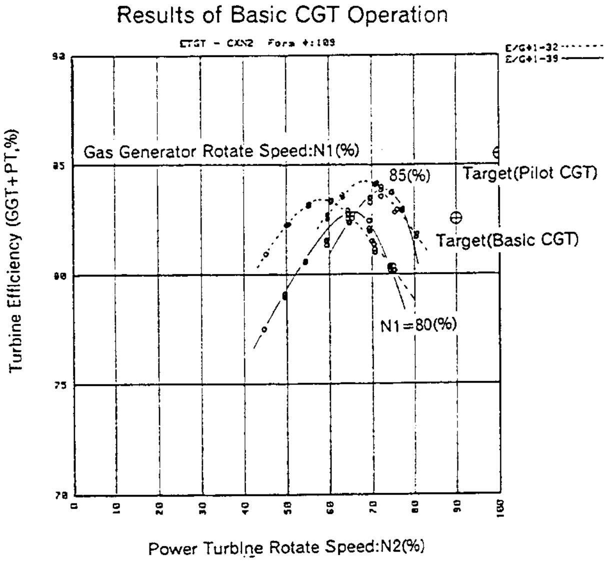


Fig. 15 Turbine efficiency in the Basic CGT

CURRENT STATE OF DEVELOPMENT OF THE CGT302 (R&D of Engine System)

Engine tests have been carried out in the steps indicated in Table 5. At this point, the CGT302 has been tested at step 4 and 5, and the accumulated operating time has attained to about 18.5 hours, including 1 hour of non-stop operation at TIT of over 1200°C, as shown in Table 5.

In the test at step 4, the CGT302 achieved 28.8% thermal efficiency at a TIT of 1117°C under ISO conditions. Achieved performance is shown in Table 1. The performance curve plotted against gas generator speed (N1) is shown in Fig. 16. The thermal efficiency deviation at the same N1 speed (ex. N1=85%) can be accounted for by the difference of power turbine speed (N2). In general, twin-spool gas turbine, like CGT302, has optimum N2 speed at arbitrary N1 speed. Fig. 17 shows the engine performance plotted in relation to the N2 speed. By extrapolating these curves in Fig. 16, we predict that the CGT302 will satisfy its target.

Fig. 18 and 19 shows the representative ceramic parts, the gas generator wheel and the power turbine blades, at the inspection after engine operation. No damage and crack was detected and all ceramic parts were fine.

The CGT302 in step 5 has not been completed yet, but 60% of N2 speed at a TIT of 1200°C has been confirmed. In the near future, CGT302 will demonstrate its performance with the full configuration in step 5.

Table 5 Engine test steps of 1200°C CGT

Step	Evaluated Ceramic Component
1	GGT Rotor
2	Scroll Ass'y, GGT Nozzle, Seal Rings
3	Step 2 + GGT Rotor
4	Step 3 + PT Nozzle, Combustor
5	Step 4 + PT Blade (Full Configuration)

Table 6 Operating time of Engine tests

TIT (°C)	Step	Operating time
1200 <	4	1 hr 47 min
	5	5 min
1100 - 1200	4	2 hr 52 min
	5	11 min
1000 - 1100	4	5 hr 59 min
< 1000	4	7 hr 38 min
Accumulated operating time		18 hr 32 min
Start / Stop ; 142 times		

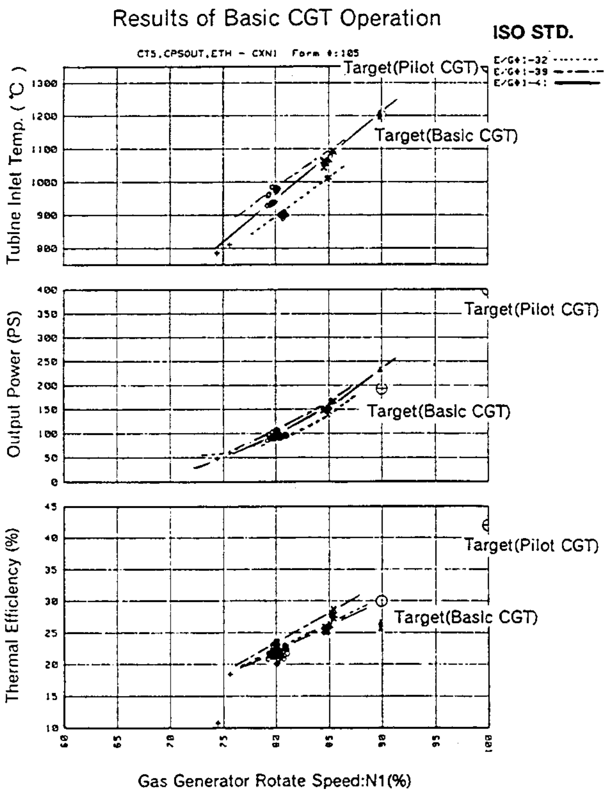


Fig. 16 The Engine performance curve plotted against gas generator speed (N1)

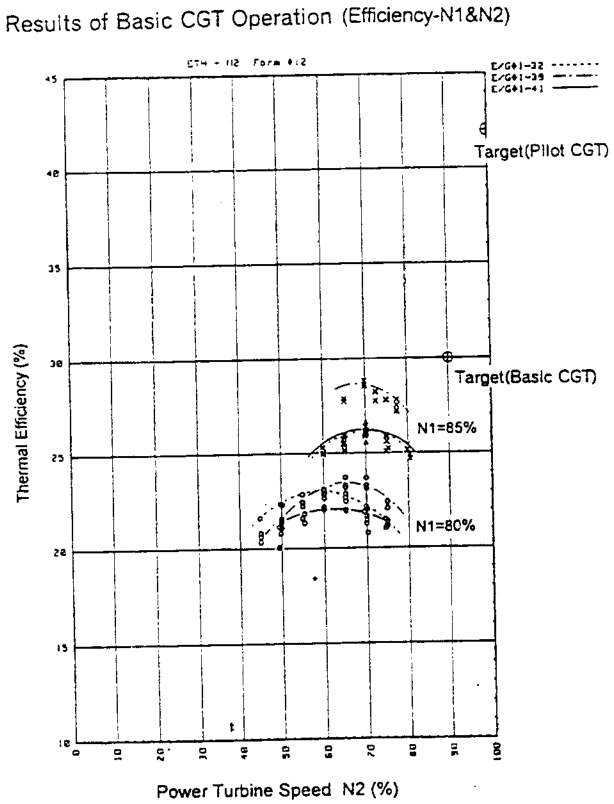


Fig. 17 The engine performance curve plotted in relation to power turbine speed (N2)

SUMMARY

1. We developed a unique technology for producing hybrid components of a Basic CGT through the trial-manufacture and evaluation of composite component models and actual composite components of a Basic CGT.

2. The CGT302 achieved 28.8% thermal efficiency at a TIT of 1117℃ with 176 PS and was confirmed to operate sufficiently at a TIT of over 1200°C.

3. The gas generator rotor was confirmed to be 101.7% rpm at an actual TIT of 1250°C with 235 PS of output power.

4. In parallel with the development of the engine system, the development of engine components is being continued. To achieve the final target for the pilot CGT, it is indispensable to satisfy each component target.

ACKNOWLEDGMENTS

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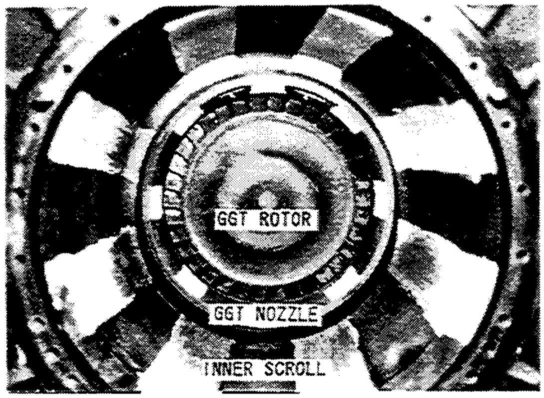

Fig. 18 Ceramic components after engine operation (Step 4)

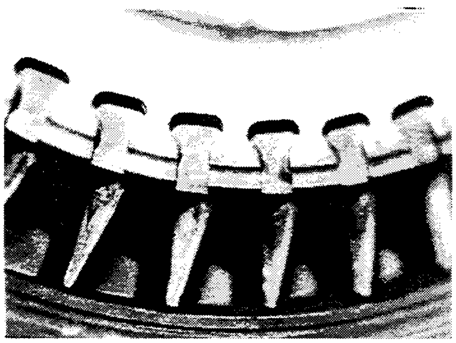

Fig. 19 Power turbine blades after engine operation (Step 5)

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