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Overview on 4 Years Achievements of Research and Technology Development of Environmentally Compatible Propulsion System for Next-Generation Supersonic Transport
(ESPR Project)

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ABSTRACT

ESPR project was initiated in 1999 with METI & NEDO support as 5 years program in the wake of precursor HYPR project. In IGTC1999-Kobe, as a precursor of ESPR project, ECO-SMART engine project was introduced and objectives, project formation and research conceptual plan were reported already (Ishizawa,1999). As for the project research objectives, in ESPR program, as environmentally compatible technologies, 3 major subjects, viz. noise suppression, NOx reduction, CO2 reduction and 4th system integration technologies are essential because they are thought as necessary conditions to realize next-generation SST propulsion system. (Ito,2000 and Tokumasu et al, 2001)

In order to fulfill the above, 2 Japanese national laboratories (NAL, AIST), 4 overseas engine makers (PWA, GE, RR, and Snecma) and 4 Japanese organizations (ESPR, IHI, KHI and MHI) have been making efforts in these 4 years with fruitful achievements. In this paper, intermediate results of these 4 years are mainly presented.

NOMENCLATURE

AIST:	Advanced Industrial Science and Technology Research Institute
ESPR(project):	Research and Development of Environmentally Compatible Propulsion System for Next-generation Supersonic Transport
GE:	General Electric Company
HSRP:	High Speed Research Program
HYPR (project):	Engineering Research for Super/Hyper-sonic Transport Propulsion System
ICAO:	International Civil Aviation Organization
IHI:	Ishikawajima-Harima Heavy Industries Co. Ltd
KHI:	Kawasaki Heavy Industries, Ltd
LPP:	Lean, Pre-vaporized and Pre-mixed
METI:	Ministry of Economy, Trade and Industry
MHI:	Mitsubishi Heavy Industries, Ltd
NEDO:	New Energy and Industrial Technology Development Organization
NAL:	National Aerospace Laboratory
NASA:	National Aeronautics and Space Administration
RR:	Rolls-Royce plc.
UTC:	United Technologies Corporation
Snecma:	Societe Nationale d'Etude et de Construction de Moteurs d'Aviation
UEET:	Ultra Efficient Engine Technology

1. INTRODUCTION

As for actual development and production of next-generation Supersonic Transport (NeG-SST), it seems unrealistic at this moment because USA/NASA stopped so-called HSRP program (Shaw, 2000) and shifted to UEET program in 1999 (Shaw, 2001). On the other hand, Supersonic Business Jet (SSBJ) is being studied even now among aircraft and aero-engine manufacturers. In civil aviation market, high speed aircraft demand is still present. In addition, Concorde will retire in October this year but post-Concorde aircraft (NeG-SST) would be realized in the future. Henceforth, it is valuable to continue technology development for NeG-SST propulsion system. Moreover, it must be necessary condition that environmentally compatible technologies will be ready for new propulsion system design and development. Therefore, under current situation, those technologies should be studied more deeply.

Here, those environmentally compatible technologies should be defined together with target values. They are

1) Noise suppression technology : ICAO Chap. 3 – 3 dB,
2) NOx reduction technology : 5 EI (g/fuel-kg),
3) CO2 reduction technology : 25% less than current technology level,
4) Engine system integration technology.

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As for research organization, Fig. 1 shows it, and as understood, international collaboration is realized as well as HYPR project.

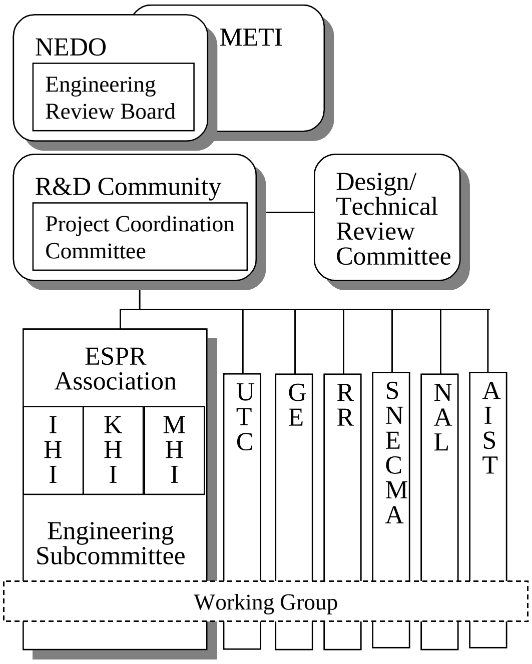


Fig. 1 ESPR Organization

2. METHDS AND PROGRAM

As stated in the papers (Tokumasu et al, 2001 and 2002), 4 major objectives are already identified and how to achieve them have been described in detail. Therefore, in this paper, they need not be duplicated and just each essence of them will be shown.

2.1 Target Engine Definition

Prior to engine description, NeG-SST aircraft should be defined. The target aircraft of NeG-SST is as follows, viz.

300 seats
M=2.2 at cruise
Range=10,200km, et al.

In order to realize 3 major objectives mentioned above, the target engine of NeG-SST should have characteristic features as shown in Fig. 2.

Some of them should be explained here. As for jet noise reduction, an axi-symmetric mixer-ejector nozzle has been chosen for the solution device because of weight reduction benefit. The array of mixer lobes can break up exhaust jet to multiple and small jets and good mixing can be followed with broadband noise remained in the ejector duct. However, that broadband noise can be suppressed effectively by acoustic attenuation liners installed on the wall of ejector duct.

Fig.3 shows the concept of the above device to suppress jet noise. From engine cycle setting, at take-off condition, exhaust velocity is about 600 m/s with aircraft speed M=0.3.

The second item is low NOx emission technology. NASA research result for ozone layer affect of NOx suggested 5 EI is at least necessary to keep it within natural fluctuation boundary. To realize 5 EI under TIT 1650C, LPP combustor (Ninomiya et al, 2001) is chosen as the solution configuration. 1/16 model (Single Sector Unit) of LPP combustor is shown in Fig. 4. As for combustor liner material, CMC is adopted to realize a benefit for NOx reduction due to less air needed for liner cooling.

The third is engine performance characteristics. In order to realize low exhaust jet speed, bypass ratio is more than 1.0 and overall pressure is around 13. On the other hand, to realize high efficiency, TIT is 1650 C with 50% reduction of turbine cooling air together with 30% weight reduction of innovative material introduction.

- **High Bypass Ratio (≧1.05)**
  (By 50% reduction of turbine cooling air
  applying advanced material and cooling)
- **Low Noise Mixer Ejector**
  (Low　Vj@TO (=600m/s))
  (By applying aerodynamically optimized noise suppressor)
  (By a pplying porous material for noise attenuation)
- **Light Weight (30% weight reduction)**
  (By applying CMC, Ti-Al, MMC)
- **LPP Combustor** (Lean Pre-mixed Pre-vaporized)

Fig.2. Feature of Target Engine

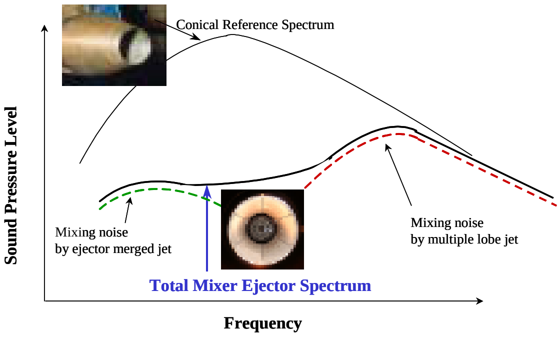


Fig. 3 Noise Reduction concept by mixer ejector

Fig. 4 Single sector of LPP combustor (1/16 model)

2.2 Research Program

Fig. 5 shows ESPR program process. Based upon the target engine, each research target of each sub-subject is identified, then analyses and validation tests should be carried out adequately and some of major research subjects should be validated on the HYPR heritage engines as shown in Fig. 5.

As final goal, their results should be integrated and evaluated on the target engine whether the original objectives can be achieved or not.

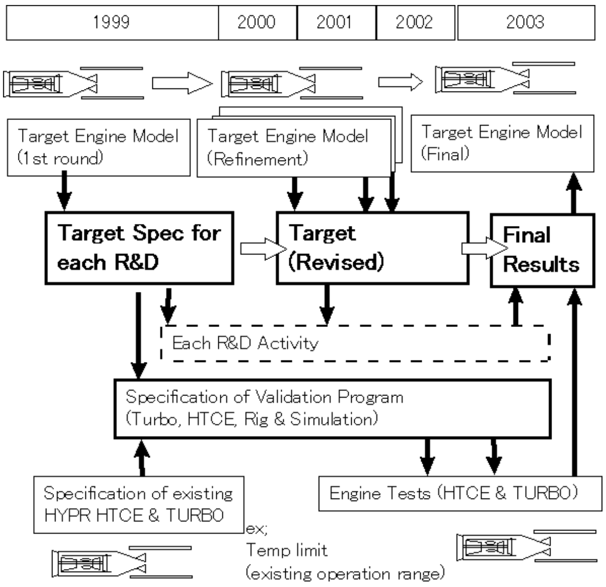


Fig. 5 Evaluation Flow of ESPR Target

3. FOUR YEARS ACHIEVEMENTS

4 years have been passed and current achievements/results will be shown as follows.

3.1 Noise Suppression

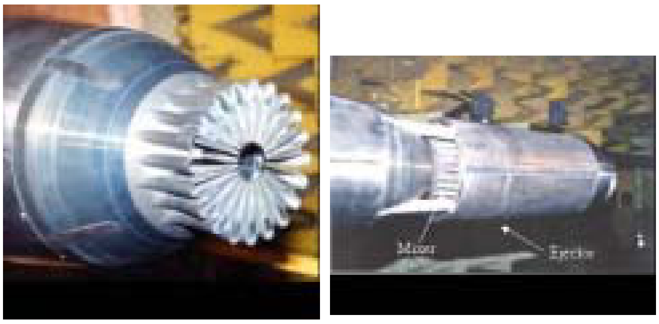
As for noise suppression, exhaust jet noise is main concern for NG-SST propulsion system. However, when exhaust jet noise becomes improved, fan noise shall be also reduced appropriately especially at flight approach condition.

3.1.1 Jet Noise.

To evaluate the flight effect on both noise and thrust loss, the scaled model test was carried out at CEPRA19 anechoic wind tunnel with acoustic and aerodynamic measurements (Fig. 6). The scaled mixer-ejector model is approximately 1/11 to the target engine and simulates an engine exhaust geometry after the turbine exit position as shown in Fig. 7. Test conditions also simulate take-off flow velocity around engine/ejector-mixer and aero-thermal conditions upstream of the ejector-mixer nozzle.

An evaluation of flight noise level in EPNL (Effective Perceived Noise Level) at sideline point was made for the assumed aircraft installing the target engine by scaling up the model test data. It was almost confirmed the target jet noise level-in other wards 3EPNdB quieter than ICAO annex 16 chapter3 for sideline noise regulation-can be achieved. Fig. 8 shows the comparison of noise spectra at the maximum PNL (Perceived Noise Level) between a conical nozzle and the mixer ejector with/without absorber-lined wall.

Fig.6 Anechoic wind tunnel (CEPRA 19)



Mixer Configuration Mixer-Ejector Configuration

Fig.7 Mixer ejector model

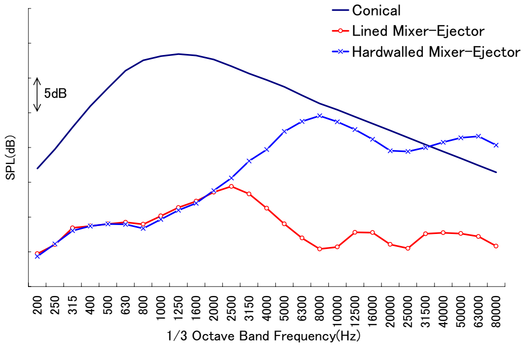


Fig.8 Noise reduction effect by mixer-ejector

3.1.2 Fan Noise.

Fan noise reduction should be achieved by the concept of swept/leaned stator vanes in the bypass duct (FEGV). It is effective to reduce fan rotor wake-stator interaction noise. Fig. 9 shows the noise reduction test results by the swept-leaned stator as shown in Fig.10. Based upon this result, 1.5EPNdB fan noise reduction compared with the straight stator vane is achieved in EPNL evaluation. This FEGV design is based upon new aerodynamic design developed by the use of unsteady RANS (Raynolds Averaged Navier-Stokes Analysis) (Tsuchiya et al, 2002).

Currently, further 1.5 dB reduction is under evaluation based upon improved aerodynamic design method. .

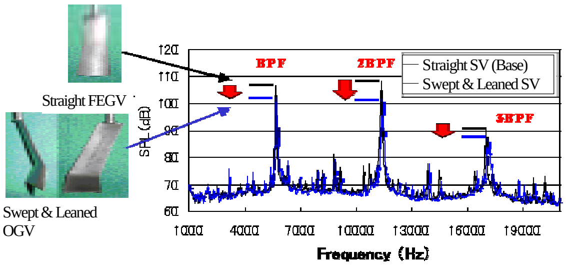


Fig.9 Noise reduction effect by swept-leaned stator

Fig.10 Model fan with swept-leaned stator

3.2 NOx reduction

NOx emissions of 5EI is set as the goal in the ESPR program. This goal corresponds to 1/7 of the value produced by existing technology and it is a challenging value to achieve for an aircraft combustor with combustor exit temperature of 1650 C.

3.2.1 LPP Combustor.

Single sector combustor tests (Fig.4) were conducted at M2.2 condition (P3 (MPa)=1.135, T3 (C)= 642, T4(C)=1650, AFR=31) to evaluate fundamental characteristics such as stable range, auto-ignition, flash back, and emissions etc. The results acquired last June showed NOx emission level of 3.8EI NOx as shown in Fig. 11. A full annular combustor test is planned next fiscal year in RR, UK for the final assessment of the low NOx combustor at M=2.2 conditon.

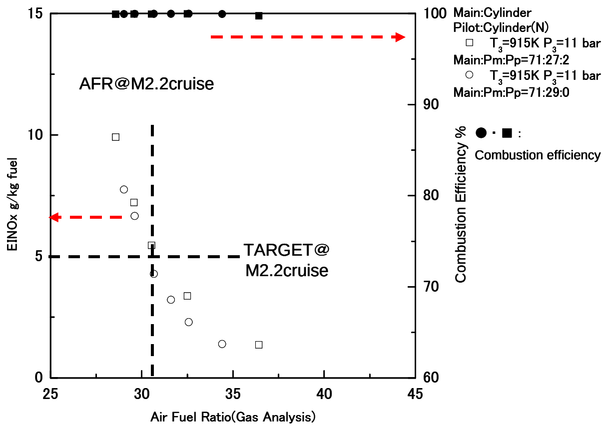


Fig. 11 Emission characteristics
(NOx and combustion efficiency @ M2.2)

3.2.2 NOx Feed-back AI Control.

The LPP combustion system can be applied to aircraft engines in which the combustor works in very wide range condition if local equivalence ratio in the combustor can be controlled according to diagnoses of combustion condition (flame temperature, emission or pressure etc.).

ESPR is also developing another combustion control system in which the air flow distribution in combustor is controlled according to measured NOx and CO emission in order to achieve stable and low NOx combustion. The model combustor rig is shown in Fig.12 , in which the air flow distribution ratio (ratio of pre-mixing air to dilution air) can be controlled. Fig.13 shows the typical result acquired through the combustion rig test, which shows the correlation between NOx and CO emissions. By using these data, the possibility to operate combustor in the condition where both NOx and CO emissions are low, will be confirmed through the feedback combustion control demonstration test.

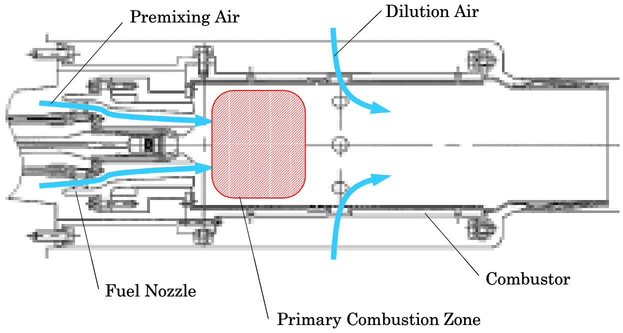


Fig. 12 Model Combustor Rig

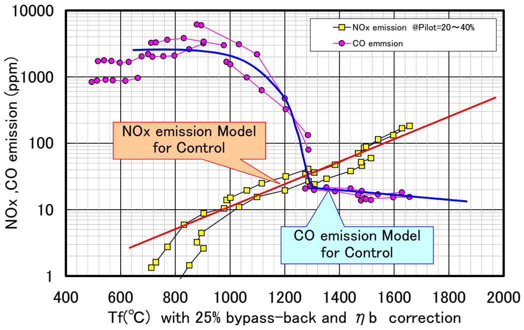


Fig. 13 Correlation between NOx emission and CO emission

3.2.3 CMC Liner.

Trial CMC combustor liners were manufactured and evaluated by combustor rig test. Fig.14 shows a CMC inner liner. This CMC liner was manufactured with Si-Zr-C-O (Tyranno ZMI) fiber as a reinforcement fiber and their preforms were woven by braiding method.

In addition, material properties of CMC were also evaluated as shown in Fig. 15, using test specimens. Those specimens were simulated the structure of the CMC combustor liner.

Fig. 14 CMC Combustor Inner Liner

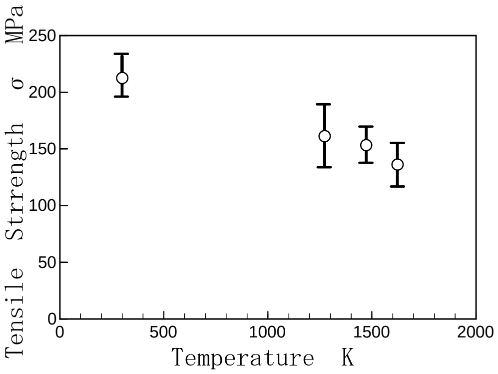


Fig. 15 Strength of CMC Combustor Inner Liner

3.3 CO2 reduction

CO2 reduction will be made by various approaches. As for engine control system approach, Takahashi et al (2001) have already presented out of their research, for example. Here, interim results of innovative light weight material applications and TBC technologies are reported.

3.3.1 TMC Fan Rotor

Fig.16 TMC Fan rotor sub-scale model ring for spin test

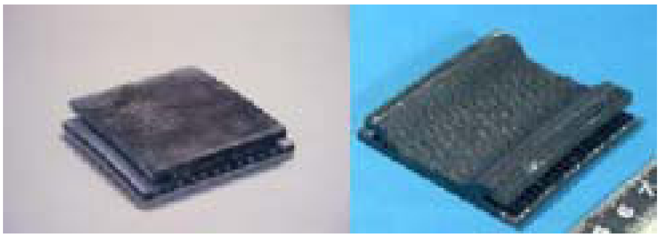
With the use of monotape preform method, TMC (Titanium Materix Composite) ring with a dimension of 130-114mm in diameter and 26mm in width was manufactured as shown in Fig.16.

The cost of TMC ring could be reduced by 60%, compared with conventional methods. Over speed tests of TMC ring has been carried out. For comparison, Ti monolithic ring with the same shape of TMC ring was manufactured and put to the over speed test.

For deformation which arises from rotational accelerated velocity, TMC reinforced specimen is less deformable than Ti monolithic one.

3.3.2 CMC Turbine Shroud.

Concerning about the CMC shroud parts, HTCE (High Temperature Core Engine) HP turbine shrouds are tried to be replaced to CMC parts. Trial CMC shrouds were manufactured. Fig. 17 shows 2 types of trial CMC shroud. First is 3 dimensional fabric type. Second is near net fabric type. Material tests, bonding strength tests and thermal cycle tests were performed to select candidates of topcoat materials. Tensile tests of joint portion were carried out with specimens of shroud configuration in order to evaluate strength of CMC shroud.



(a)3D fabric with coating (plane fabric)

(b)Near net shape fabric

Fig. 17 2types of trial CMC shoroud

As for CMCs (Ceramic Matrix Composites), the embrittlement caused by interface oxidation at elevated temperature is one of the key issues. For SiC/SiC, to improve the oxidation resistance, inhibitor was added to the polymer precursor, which forms the matrix. Result of improvement was shown in Fig. 18. The creep rupture property of this oxidation resistant SiC/SiC was remarkably improved. The stress level of about 100 (MPa) was accomplished in strength on the temperature condition of 1473K.

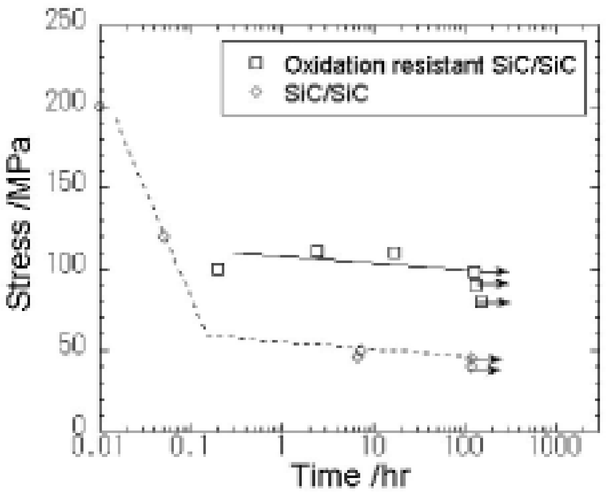


Fig. 18 Creep rupture data of CMC (at 1473K, in air)

3.3.3 TiAl Shroud Support.

A cast gamma titanium aluminide (TiAl) high pressure turbine shroud support for HTCE was manufactured. Ti-48Al-2Cr-2Nb alloy was chosen because it offers a relatively good balance of castability, mechanical properties, and economy. This demonstration component was a complex geometry ring about 760mm in diameter. 25mm thick, and 64mm long. Key issues include thermal expansion mismatch of TiAl and mating nickel-based parts, the temperature capability of TiAl, and development of suitable casting and machining processes. A weight reduction was achieved in excess of 50% relative to the current Ni-based part. Fig. 19 depicts successful TiAl shroud support.

Fig. 19 TiAl shroud support for HTCE test

3.3.4 TBC Technology.

TBC (Thermal Barrier Coating) Technology has been studied, applied to HPT blades and was validated in HTCE engine. By the way, top coat material is YSZ (Yttria stabilized Zirconia) and process is APS (Air Plasma Splay). On the other hand, bond coat material is CoNiCrAlY and process is LPPS (Low Pressure Plasma Splay).

4. ENGINE TEST VALIDATION - HTCE TEST RESULTS

HTCE engine was assembled and tested. Newly developed parts such as TiAl shroud support, TBC turbine blade, pyrometer and FADEC were incorporated into HTCE engine as shown in Fig. 20. The HTCE test objectives were the validation of those parts to confirm functional and structural soundness. The test was carried out on the condition of holding TIT (Turbine Inlet Temperature) 1650 C during 15 minutes.

Fig. 21 shows the results of TiAl shroud support temperature measurements. The all of monitored air and metal temperatures did not exceed the engine operation limit value during test and coincided well with the heat transfer theoretical analysis. The maximum temperature slope ($\Delta T/\ \Delta t$) in engine testing was slower than that in the rig test which was done to confirm the thermal cycle resistance prior to engine test.

After the test, engine disassembly and visual inspection were conducted and no obvious damage was found out. Fig. 22 shows the parts after the test. Thermal color said that the maximum metal temperature of the front hook was approximate 600 C (873 K), which is corresponding to the thermocouple data.

Fig. 23 and 24 show the results of smart sensor (pyrometer). Each of all blades temperature could be measured and 2-D temperature distributions were obtained on the condition of TIT 1650 C. Output difference between the pyrometer and thermocouples was less than ±10 C.

As for TBC technology, Fig. 26 show the result of TBC coated HPT blade compared with the initial feature after the test. The concerned parts are quite sound.

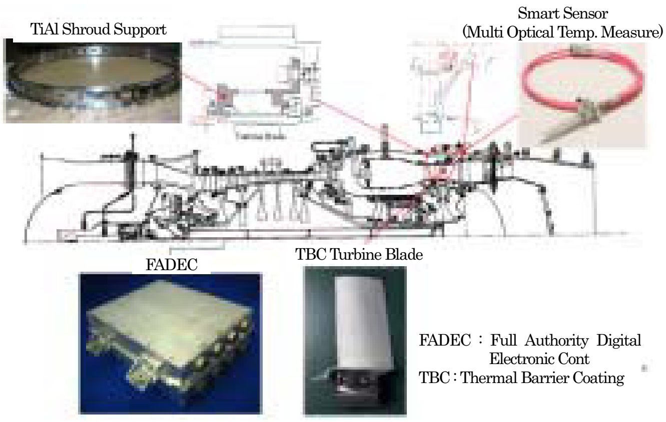


Fig. 20 Incorporated parts into HTCE

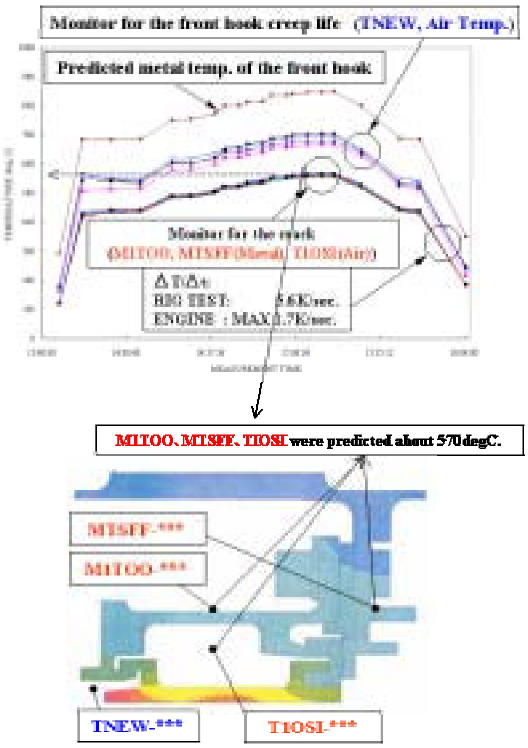


Fig. 21 Temperature behavior about TiAl shroud support at engine test

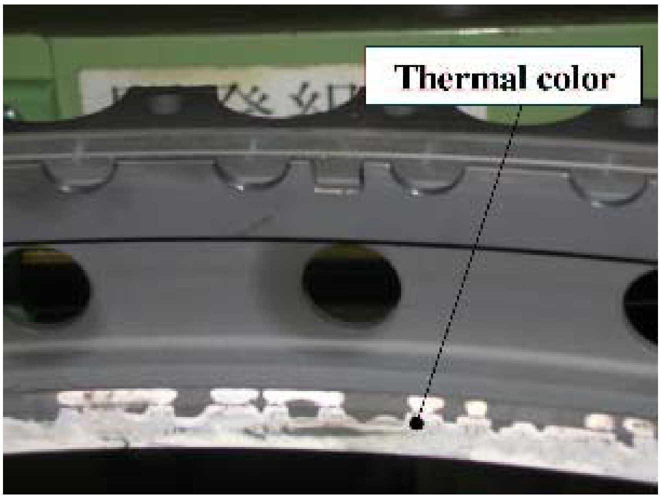


Fig. 22 TiAl shroud support after the test

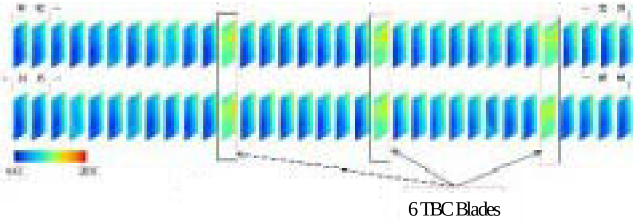


Fig. 23 Smart Sensor (Pyrometer) results

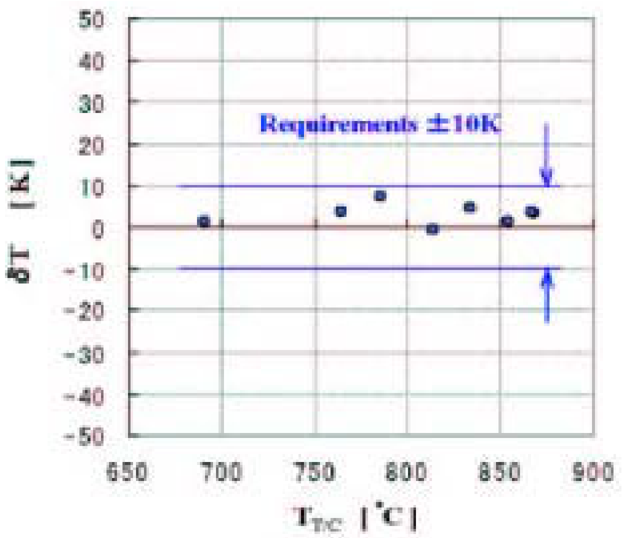


Fig. 24 Thermocouple vs. Smart Sensor (Pyrometer)

Before the Test After the Test

Fig.25 TBC coated HPT Blade

5. FUTURE PROGRAM

As stated in the Introduction, final year of the program started in April, 2003. The 3 major tests should be carried out.

5.1 Engine Test

As for engine tests using HYPR heritage turbojet and HTCE engine. The turbojet engine is now (in Aug. 2003) running to carry out ejector-mixer jet noise suppression validation test at UTC–Florida Facility. ICAO Chap. 3-3dB (@sideline) should be confirmed experimentally.

On the other hand, HTCE will carry out validation test for several parts/hardware of CO2 reduction technologies, for example, CMC turbine shroud, TBC-blade of HP turbine, PM disc etcl.

This test is planned in Feb. 2004 as final test of ESPR program.

5.2 Component Tests

A number of rig and material tests are planned in this fiscal year, but the most important test is LPP full annular test in December which will be carried out in RR in order to achieve 5 EI without combustion instabilities like flash back, auto ignition and combustion oscillation.

After all the tests and analytical studies, all the data should be got together and evaluate whether they satisfy the original target engine specification or not.

6. ACNOWLEDGEMENT

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