Research and Technology Development of Environmentally Compatible Propulsion System for Next Generation Supersonic Transport (ESPR Project) III. Final Achievements

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Abstract

ESPR project initiated in 1999 with METI and NEDO supports as 5 years program in the wake of precursor HYPR project. In ICAS2002-Toronto, Intermediate achievements were reported and project objectives, formation and research conceptual plan were presented already. As for the project research objectives, in ESPR program, as environmentally compatible technologies, 3 major subjects, viz. noise suppression, NOx reduction, CO2 reduction technologies and 4th system integration technologies are essential because they are thought as necessary conditions to realize Next-Generation SST propulsion system.

In order to fulfill the above, 2 Japanese national laboratories (JAXA, AIST), 4 overseas engine makers (PWA, GE, RR, and Snecma) and 4 Japanese organizations (ESPR, IHI, KHI and MHI) have been making efforts during project period, viz. 5 years with fruitful achievements. In this paper, final achievements of these 5 years are presented.

Abbreviation

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 Aircraft Engines Co.
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
JAXA: Japan Aerospace Exploration Agency
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
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

5 years have passed since ESPR project started just after HYPR project [1,2] under Japan Government (METI) and NEDO supports. Although the precursor HYPR project aimed M5.0 Hypersonic Transport, ESPR project focused M2.2 Next-Generation Supersonic Transport (NeG-SST) Propulsion System.

However, as for actual development and production of NeG-SST, it seems unrealistic at this moment because no movement of developing post-Concorde aircraft exists among the world although the Concorde was retired last October. Furthermore, big scientific programs on NeG-SST Technologies other than ESPR project have not survived after USA/NASA stopping so-called HSRP program[3] and shifted to UEET program in 1999 [4].

On the other hand, Supersonic Business Jet (SSBJ) is being studied now among aircraft and aero-engine manufacturers. In civil aviation market, high speed aircraft demand is still present. In addition, it is anticipated around 2015 post-Concorde aircraft would be realized in the world. Henceforth, it is valuable to continue technology development for NeG-SST propulsion system.

Until actual NeG-SST realization, it must be necessary that environmentally compatible technologies for noise, NOx and CO2 reduction should be ready for new propulsion system design and development. Therefore, under current situation, those technologies should be studied more eagerly.

Here, targets of those environmentally compatible technologies should be defined as follows,

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 in 1999,
4) Engine system integration technology.

As for research organization, international collaboration among 8 organizations (ESPR, IHI, KHI, MHI, GE, UTC, RR, Snecma, JAXA, AIST) works as well as HYPR project.

2. Method and Program

As stated in the papers [5,6], 4 major objectives are already specified and how to achieve them have been described in detail. Therefore, in this paper, each essence of them will be described.

2.1 Target Engine

Prior to target 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. 1.

As for jet noise reduction, an axially-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 .2 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 is chosen as the solution configuration. AS shown in Fig. 3, an axially staged combustor with a combination of an LPP combustion system and CMC liner walls is adopted. The usage of heat resistance material of CMC has 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 12. 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.1. Feature of Target Engine

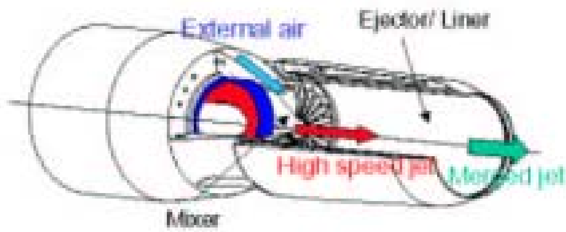


Fig. 2 Mixer Ejector Concept

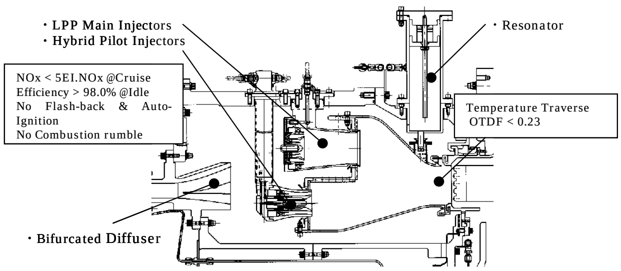


Fig. 3 Feature of LPP combustor

2.2 Research Program

ESPR program process was introduced in [5~8]. 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 [5~8]. As final goal, their results should be integrated and evaluated on the target engine whether the original objectives can be achieved or not.

As for rig test validation program, LPP combustor research and validation process is shown ,for example, in Fig.4.

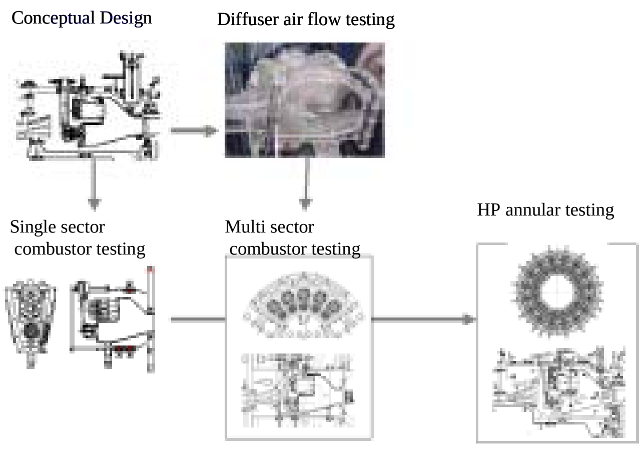


Fig. 4 Research and Evaluation Flow of LPP combustor

3. Final Achievements

5 years have passed and final achievements/results will be shown as follows.

3.1 Noise Suppression

As for noise suppression, exhaust jet noise is main concern for NeG-SST propulsion system. However, when exhaust jet noise becomes improved, fan noise shall be also reduced appropriately especially at flight approach condition. Both of jet and fan noise should be reduced by 3 dB respectively.

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. The scaled mixer-ejector model is approximately 1/11 to the target engine and simulates an engine exhaust geometry after the turbine exit position. The details were reported in [7,8].

Final validation test was carried out by using HYPR heritage turbo-engine with mixer-ejector installed at UTC Florida. Test scenery is shown in Fig.6, which shows noise barrier wall. At the engine intake, TCS (Turbulence Control System) was also equipped and mixer and mixer-ejector configuration are shown in Fig. 7 and Fig. 8.

One result is presented in Fig. 9. Detailed analyses of test data can guarantee achievement of 3.1 dB reduction from ICAO Chapter 3 of jet noise on Target Engine/SST aircraft combination

Fig.6 Engine Noise Test (UTC-Florida)

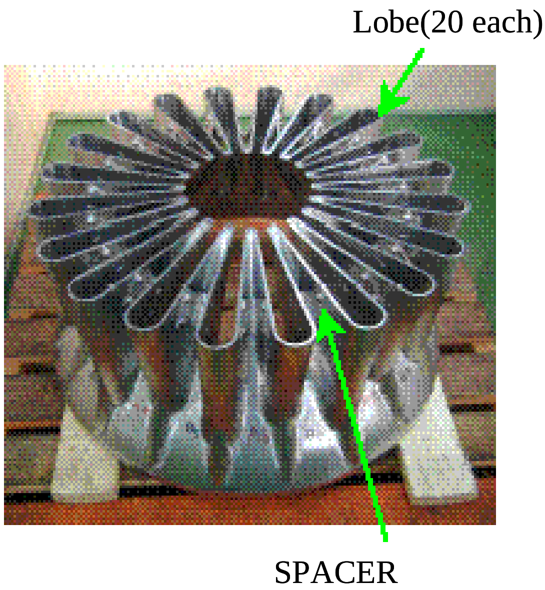
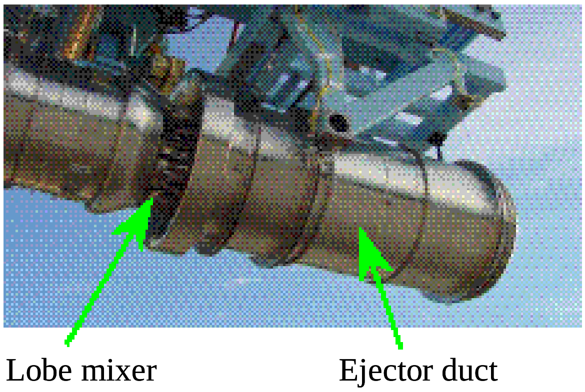


Fig. 7 Mixer Configuration



Fig, 8 Mixer-Ejector Configuration

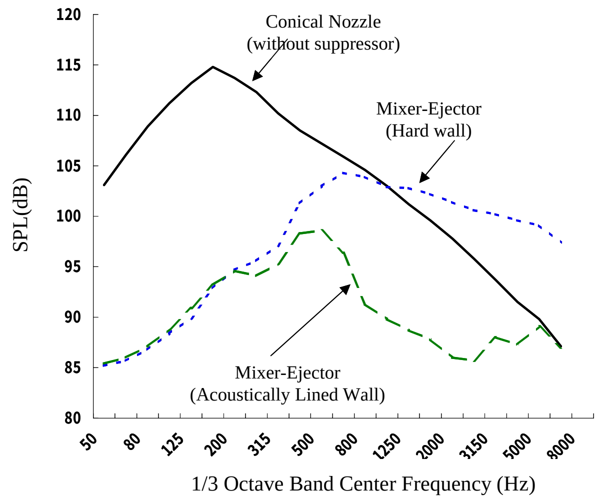


Fig.9 Evaluation of Noise reduction Characteristic by Mixer-Ejector

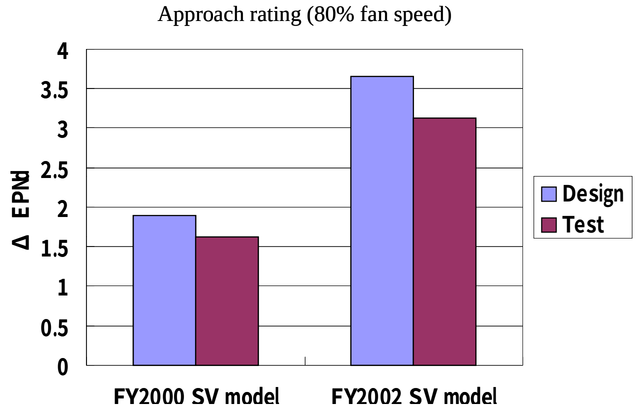


Fig.11 Noise Suppression Effect of 2002 Model Swept-Leaned Stator

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. For the results of initial design of FEGV was reported in [9]. At that time, 1.5dB reduction was achieved. Then, 2002 model was designed as shown in Fig. 10. The lean and swept feature are different from 2000 model significantly. Analytical prediction and experimental results can endorse 3 dB reduction of fan noise as shown in Fig.11. This results was reported in detail in [10]

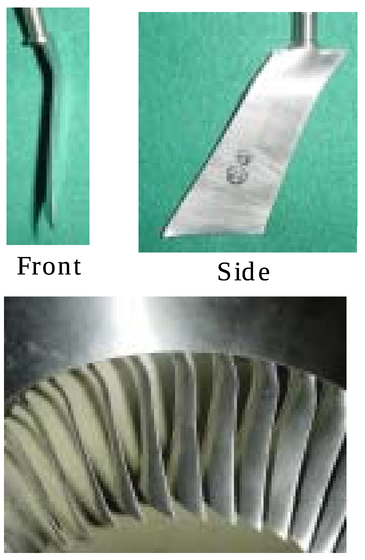


Fig. 10 2002 Model Fan with swept-leaned stator (2002 Model)

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.3) to evaluate fundamental characteristics such as stable range, auto-ignition, flash back, and emissions etc were conducted and intermediate results were already reported in [11,12,13]. The latest results of single sector test at M2.2 condition (P3 (MPa)=1.135, T3 (C)= 642, T4(C)=1650, AFR=31 acquired last June showed NOx emission level of 2.7EI NOx as shown in Fig.12. A full annular combustor test was carried out in RR, UK for the final assessment of the low NOx combustor at M=2.2 condition as shown in Fig. 13. The result, under 0.9MPa pressure, shows about 3 EI without any combustion instability such as auto-ignition, flash back and combustion Oscillation.

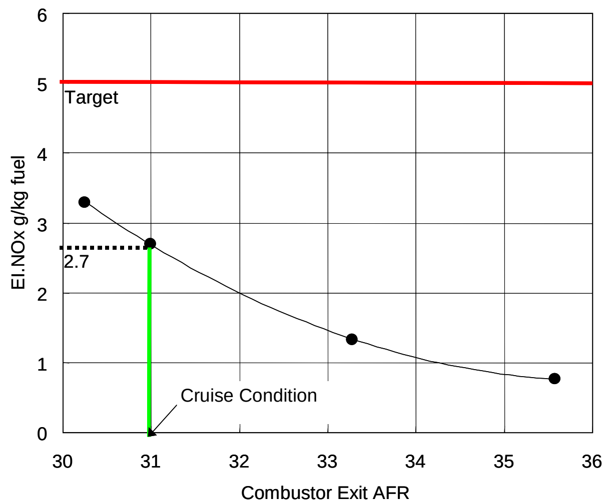


Fig. 12 Emission characteristics (NOx and combustion efficiency @ M2.2)

Fig. 13 Full Annular Combustor Test

3.2.2 NOx Feed-back AI Control

In ESPR project, another combustion control system has been developed in which the air flow distribution in combustor is controlled according to measured NOx and CO emissions. The combustion control test system is shown in Fig.14, in which the dilution air ratio (ratio of dilution air to total air) can be controlled according to CI(Control Index), where CI is a newly introduced fuzzy evaluation function which consists of both measured NOx and CO emissions.

A combustion control demonstration test shows that NOx was successfully maintained at a low level in spite of fuel step increase as the result of effective combustion control as shown in Fig. 15.

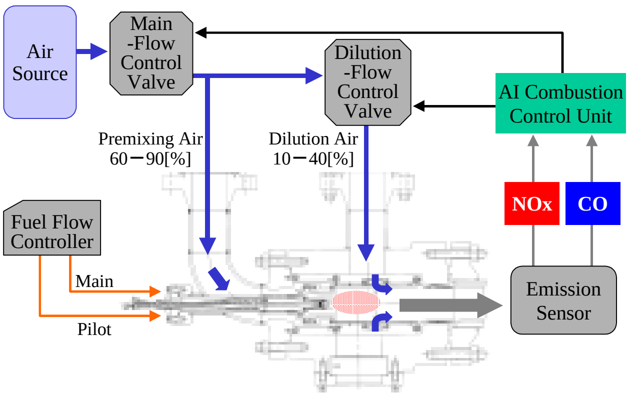


Fig. 14 Combustion Control Test Syatem

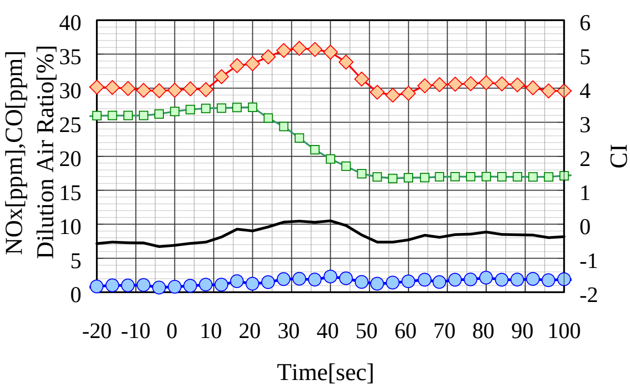


Fig. 15 Step Response to Fuel Increase

3.2.3 CMC Liner

Trial CMC combustor liners were manufactured and evaluated by combustor rig test. Fig.16 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. 17, using test specimens. Those specimens were simulated the structure of the CMC combustor liner.

Fig.16 CMC liner after combustion test

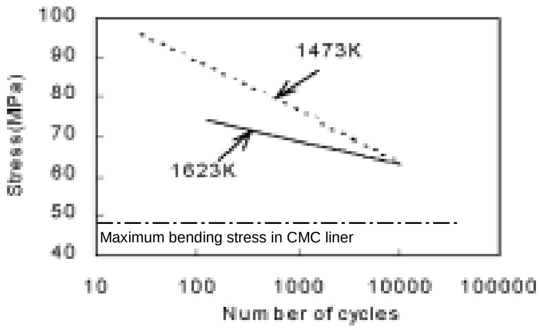


Fig.17 Low cycle fatigue property of CMC

3.3 CO2 reduction

CO2 reduction will be made by a number of various approaches. As for engine control system approach, Takahashi et al [14] have already presented early out of their research, for example. However, here, results of innovative light weight material applications and TBC technologies etc are reported.

3.3.1 TMC Fan Rotor

As final test, burst test has been carried out as show in Fig.18. Burst fragments of small size ring under 2000 LCF test for confirmation of relationship to LCF results of test piece and the test data shows quite coincident to previous test piece data. By using these relationship between spin test data of small size ring and test piece data, larger disk in HYPR size of 500mm in diameter has been designed, manufactured as shown in Fig. 19 and verified soundness through 121% over-speed test.

Fig.18 TMC Fan rotor sub-scale model ring for spin test

Fig. 19 TMC Fan Rotor with HYPR Engine Scale

3.3.2 CMC Turbine Shroud

Concerning about the CMC shroud parts, HTCE HP turbine shrouds are tried to be replaced to CMC parts. Trial CMC shrouds were manufactured. Fig. 20 shows trial CMC shroud of dimensional fabric type. This CMC shroud size was about 50mm×50mm. Material tests, bonding strength tests and thermal cycle tests were performed to confirm soundness. Tensile tests of joint portion were carried out with specimens of shroud configuration in order to evaluate strength of CMC shroud. Final evaluation was made on HTCE #2 test.

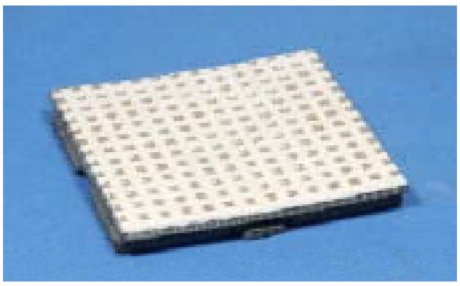
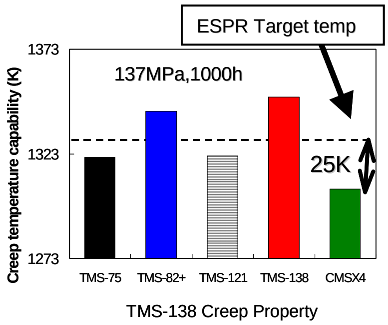


Fig. 20 CMC Turbine Shroud

3.3.3 TM-138 Turbine Blade

Single crystal turbine blade was also developed with full cooled film cooling holes as shown in Fig. 19. SC material is so-called TMS-138, which was invented and developed in Japan. Fig. 21shows the creep temperature of TMS-138 as measured at 137MPa after 1000hours of operation. TMS-138 has an advantage of temperature 37K higher than CMSX-4, which is a second generation single crystal alloy.



TMS-138
Turbine Blade

Fig. 21 TMS-138 Turbine Blade

3.3.4 TiAl Turbine Shroud Support

A cast gamma titanium aluminide (TiAl) high pressure turbine shroud support 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 etc. Weight reduction was achieved in excess of 50% relative to the current Ni-based part. Fig. 22 depicts successful TiAl shroud support.

Fig. 22 TiAl Shroud Support for HTCE Test

3.3.5 TBC Technology

TBC (Thermal Barrier Coating) Technology has been studied, applied to HPT blades and validated in HTCE #1 test. By the way, on HTCE #1 test, 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).

On the other hand, top coat process was improved from APS to EB-PVD on CMSX-4 original HYPR turbine blades and tested again on HTCE #2 test.

Results was quite good and promising for practical engine incorporation.

3.3.6 CO2 Reduction Summary

In ESPR Project, advanced control technologies ware also developed as described in [14] to get closer working line to the surge line and closer tip clearance together with smart sensor [7].

Conclusively speaking, CO2 reduction target, -25% from 1999 technology level, was achieved as shown in Fig. 23. Weight reduction was made up to 29.5% against the target 30% and cooling airflow reduction 56 % against the target 50%. This means CO2 reduction is 29 % as a result.

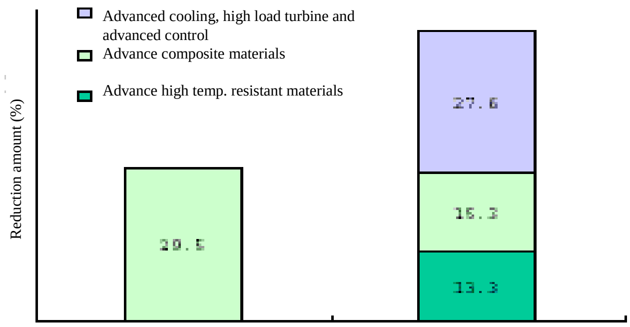


Fig.23 Reduction of engine weight and cooling airflow

4. Engine Test Validation

4.1 HTCE #1 Test

HTCE engine was assembled and prepared for #1 engine test. Newly developed parts such as TiAl shroud support, TBC turbine blade, pyrometer and FADEC were incorporated into HTCE engine. Fig. 24 shows incorporated parts into HTCE for #1 test. The HTCE #1 test objectives were the demonstration of the developed parts and confirmation of functional, structural soundness. The test was carried out safely on the condition of holding TIT (Turbine Inlet Temperature) 1650 C during 15 minutes as shown in Fig. 25.

The details of the results were reported in [8,9,15].

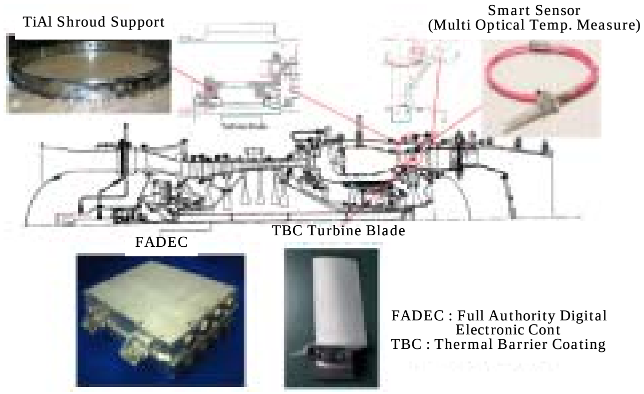


Fig. 24 Incorporated parts into HTCE #1 Test

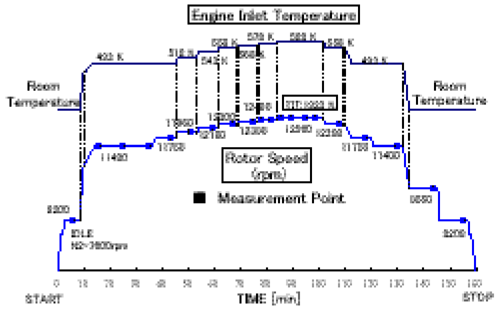


Fig. 25 HTCE Engine Test Schedule

4.2 HTCE #2 Test

On the other hand, HTCE engine also carry out #2 validation test for parts/hardware of CO2 reduction technologies, for example, CMC turbine shroud, TBC-blade of HP turbine, PM disc and TMS-138 Turbine Blade with almost same engine operation schedule. The detail results were reported in detail in [15].

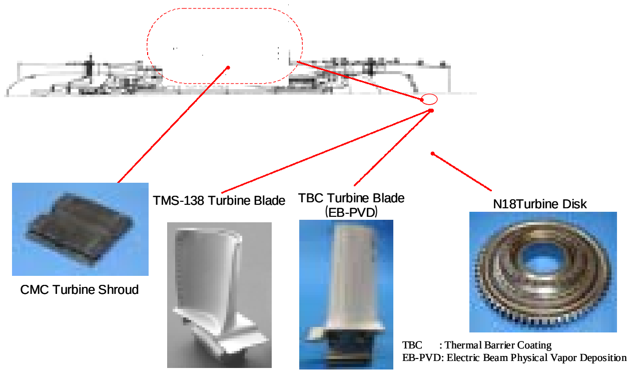


Fig. 26 Incorporated Pars into HTCE #2 Test

4.3 Turbo-Engine Noise Tests

HYPR heritage turbo-engine was used for engine noise test as described in 3.1.1. Here, the photograph of lined ejector-mixer is shown in Fig. 27.

. The details of the results have been described in 2.1 above.

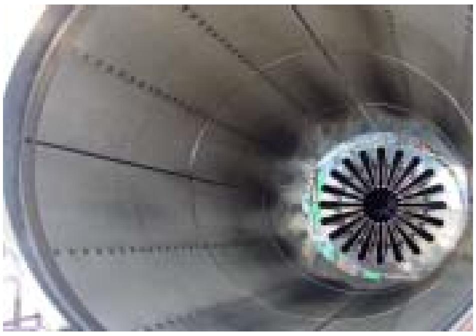


Fig. 27 Lined Mixer-Ejector after testing

5 Target Engine Evaluation

After all the tests and analytical studies, all the data were got together and evaluate whether they satisfy the original target engine specification or not. System integration technologies will play a essential role to trade-off controversial or contradictory results/data.

5.1 Target Engine Optimization

Target engine was analyzed to get the optimal TOGW(take-off gross weight) and take-off length as a function of exhaust jet velocity. Results are shown in Fig. 28 and Fig. 29, which indicate best jet velocity should be 550 m/s.

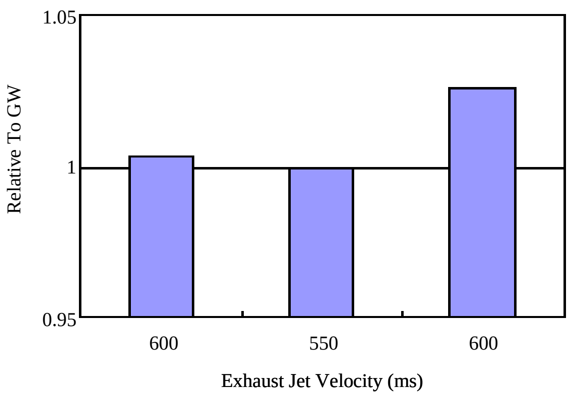


Fig.28 TOGW & Exhaust Jet Velocity

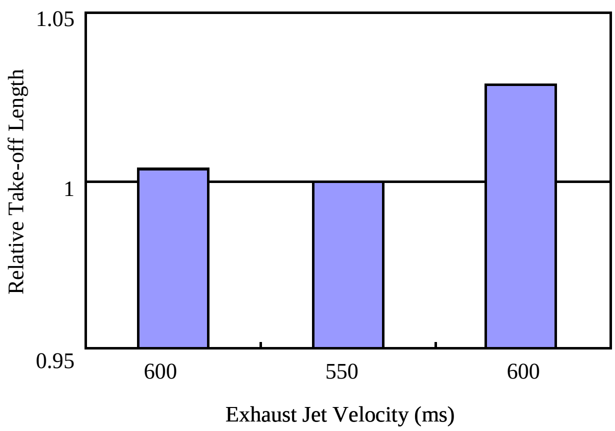


Fig.29 Take-off Length & Exhaust Jet Velocity

5.2 Target Engine Cross Section & Performance Characteristics

Target engine cross is shown in Fig. 30. Fan diameter is 2m and engine + mixer-ejector length is 12.6m.

On the other hand, engine should have the capability of variable cycle in order to get BPR change between take-off and cruising condition. As shown in Fig. 31.

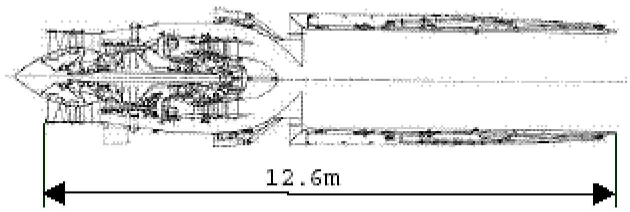


Fig. 30 Target Engine Cross Section

Item	M2.2	Takeoff
BPR	1.18	1.22
TIT	1923K	1721K
OPR	12.8	20.3

Fig. 31 Target Engine Performance

6. Conclusion

ESPR project can achieve below project targets, viz.

1)Noise Suppression: ICAO Chap.3-3dB(@sideline)

2)NOx reduction : 5 EI

3)CO2 reduction : 25%+more

4)System Integration capability.

Finally, following 2 points should be emphasized.

The first point is above achievement can encourage to realize NeG-SST although further improvement and refinement of the concerned technologies for performance upgrading, long life and higher reliability and cost down are needed. In other words, continuous technology development will be requested.

The second point is although NeG-SST may not be realized soon, above environmentally compatible technologies will be applied very well not only to subsonic aircraft engines but also to industrial gas-turbines.

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