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The Development of LPP Combustor for ESPR

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ABSTRACT

A low emission combustor aiming at 5EI NOx for a supersonic aircraft engine has been being developed under ESPR (Research and Development of Environmentally Compatible Propulsion System for Next-Generation Supersonic Transport) program in Japan. An axially staged combustor with an LPP combustion system and CMC liner walls is used for stable combustion and low NOx emissions.

Fuel injector tests and single sector combustor tests up to M2.2 cruise conditions for several types of fuel injectors have been conducted to evaluate fundamental characteristics such as emissions, auto-ignition, flash back and things since the program started.

The latest test results showed that the LPP burners had a good potential for the low NOx target. It was found that the NOx emission level was greatly affected by a distortion in the air velocity field upstream of the LPP burners due to the diffuser and fuel feed arm.

This paper is the second report on the LPP combustion system. It covers the latest research activities and countermeasures for a further NOx reduction toward the target.

NOMENCLATURE

CMC	: Ceramics Matrix Composite
EI	: Emission Index g/kg fuel
FAR	: Fuel Air Ratio
HTCE	: High Temperature Core Engine
LPP	: Lean Premixed Pre-vaporized
P_3	: Combustor inlet pressure MPa
T_3	: Combustor inlet temperature K
T_4	: Mean combustor exit gas temperature K
W_{31}	: Combustor inlet air flow rate kg/s

INTRODUCTION

Supersonic aircraft are supposed to cruise in the stratosphere during supersonic flight, hence the effect of NOx emissions from the engines to ozone layer is concerned. NASA research results show that the NOx emissions exhausted from super sonic aircraft engine should be less than 5EI at cruise conditions to protect the ozone layer (Shaw, 1993). Hence, 5EI is set as the NOx emission target in the ESPR program. This goal of 5EI NOx is a challenging to achieve for an aircraft combustor of an inlet and exit temperature of as high as 915 K and 1923 K, respectively and the goal corresponds to 1/7 of the level predicted for an existing combustion technology with a diffusion flame.

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Figure 1 shows the engine being studied in the ESPR program (The engine is called “Target engine”). An LPP combustion system is considered to be one of the best key technologies for low NOx emissions. And the use of heat resistance material of CMC for combustion liners has a benefit for NOx reduction due to less air necessary for liner wall cooling. Hence, an axially staged combustor with a combination of an LPP combustion system and CMC liner walls is applied to the combustor (Figure 2). This LPP low NOx combustion system has been being developed in collaboration among NAL, RR and KHI in this program.

The research and development plan is shown in Figure 3. In the final year of the program, a high pressure full annular combustor test is planed to evaluate the LPP combustion characteristics such as emissions, auto ignition, flash back, light across and combustion instability along the engine operation line being studied in the ESPR program (Figure 4).

NOx emissions exponentially increase with temperature and therefore combustion regions must be kept under a certain mean temperature level without locally high temperature regions. This can be achieved by lean premixed, pre-vaporized and homogeneous mixture produced by burners. For the sake of suitable mixture, LPP burners are to be developed through burner and single sector test to assess the potential for low NOx, non auto-ignition, and non-flashback. Then multi sector combustion tests follow to assess other combustion characteristics such as light across, combustion instability and temperature traverse.

Up until now, burner combustion tests and single sector combustor tests have been conducted up to M2.2 conditions to evaluate fundamental characteristics. The latest test results showed that the LPP burners had a good potential for the NOx target and that NOx emission level was greatly affected by a distortion in the air flow velocity field upstream of the LPP burners due to the diffuser, fuel feed arm and so on.

This paper covers the latest research activities as described above and countermeasures for a further NOx reduction toward the target NOx value.

COMBUSTOR DESIGN

The ESPR LPP staged combustor is shown in Figure .2. The main features are (1) an axially staged combustor with 870 mm outer diameter and 440 mm inner diameter, (2) LPP & diffusion hybrid pilot burners (16 off), (3) LPP main burners (16 off), and (4) a bifurcated diffuser. The combustor dimensions have been determined to be able to install the combustor into the existing HYPR HTCE demonstrator engine. Therefore the following items are the same as the HYPR HTCE demonstrator.

(1)Interface to the compressor exit and the turbine inlet
(2)Combustor module length (536 mm)
(3)Pre diffuser length and diffuser strut shape

(4)Inner casing diameter
(5)Number of fuel nozzles

COMBUSTION TEST RESULTS

Firstly, burner combustion tests were conducted to evaluate burner potential itself with the unit (Figure 5) without diffuser and fuel feed arm that should exist in actual engines. Following the burner tests, in order to assess emission characteristics in an engine, tests have been done with the combustor unit (Figure 6) simulating the engine configuration. The combustor has a diffuser, a robust feed arm to withstand a vibration when an engine is in operation. Either test was done up to M2.2 conditions at the high-temperature and high-pressure test facility at NAL. Both units are 1/16 models of the full annular combustor.

The material of the liner walls is not CMC but heat resistant metal of HA188. The cooling scheme is a transpiration type. The amount of cooling air is 18 % based on an airflow measurement. Firebrick is used for the sidewalls of the unit.

Burner potential assessment

Figure 7 shows NOx and combustion efficiency obtained for the unit shown in Figure 5 at M2.2 cruise inlet pressure and temperature conditions as a parameter of primary AFR. The fuel split into the main, pilot LPP, and pilot diffusion is kept the same through the tests and the split was examined to minimize NOx emission at the specified AFR at M2.2 conditions. The results show NOx emission of 3.8EI NOx at the primary AFR of 25.4 based on 18 % cooling air in this unit (AFR 25.4=AFR 31 x (1-0.18)).

Considering that the test was performed with metal walls that need a certain amount of cooling air, the tested burners have a good NOx potential to achieve the target. Combustion efficiency is very close to 100 % and there was no sign of flash back or auto ignition.

Single sector test results

Although the good burner potential has been acquired through the burner tests described the above, combustion characteristics in an engine combustor can be sensitive to flow field near the burner inlet such as an air velocity distribution caused by diffuser, and wakes from objects upstream of burners. Those flow distortions make the fuel/air mixing property worse and also induce undesirable flow fields in the pre-mixer duct for prevailing against flash back and auto ignition.

The tests have been done with the combsutor unit with a bifurcated diffuser and a pilot burner fuel feed arm (30 mm diameter) just upstream of the main burners (Figure 6). Figure 8 shows NOx emission characteristics as a parameter of primary AFR. The fuel split into main, pilot LPP and pilot diffusion is determined in the same manner as stated above. At M2.2 cruise conditions (AFR=25.4), it gives 16EI NOx which is much higher than that in the “clean” combustor described above that has no diffuser and no feed arm fitted. The flow field just upstream of the burners seems to have a great impact on NOx emission characteristics and thus a great care should be taken to design a suitable flow field in front of burners.

The causes that make NOx emissions worse have been investigated. Figure 9 shows the NOx emission characteristics without the diffuser tested in the same condition as Figure 8. Based on the result, the NOx level hasn’t changed much or it is slightly lower with the diffuser. The air flow distortion caused by the diffuser is supposed to give a worse mixing property in terms of uniformity in radial direction, hence it created less homogeneous flame temperature region in the primary combustion zone. On the other hand, the total air feed into the burners gives more air going through the burner and that result in lower flame temperature in average. In this test, these two effects on NOx emission are supposed to cancel each other and that result in the similar NOx value.

Figure 10 shows NOx emission level tested in the combustor with a reduced pilot feed arm. The diameter of feed arm is originally 30 mm and in this test the parts simulating the arm is removed. Only thin fuel feed pipes (about 6 mm) are exposed and they are located at just upstream of the main burner. The NOx value at 25.4 AFR has gone down from 16EI to 9EI. The wakes from the objects just upstream of main burner is supposed to have a great effect on NOx value.

When the diffuser and the feed arm simulating parts are removed, the combustor configuration becomes very similar. The specifications of swirl vanes and fuel injection holes were identical between two models except for fuel feed pipe arrangements But comparing the test results shown in Figure 7 and Figure 10, there still seems to have a big difference between two models. The causes for the difference are now under investigation.

COUNTERMEASURES TO ACHIEVE THE TARGET

The following three items are to be considered for a further NOx reduction toward the target.

(1) Minimize wakes to main burners

As already mentioned above, the wakes from the objects, especially the pilot feed arm, located upstream of burners have a great impact on NOx emission level. To minimize wake generation just upstream of the mains, a “Dog leg“ feed arm shown in Figure 11 is planned to employ to the combustor. With the “Dog leg” feed arm, it is expected that NOx will goes down to 9EI as shown in Figure 12.

(2) Cooling air reduction

CMC material is originally planned to install into the full annular combustor test for the final assessment. Due to its strength problem, however, metal liner walls combustor is to be used instead of CMC walls. A shallow angled effusion-cooling scheme is employed for the metal liner due to its potential of the cooling effectiveness.

The liner is 3 mm thick with heat resistant material (C263) and effusion holes are 0.6mm in diameter with the angle of 17degree. Thermal paint tests (OG-6 Thermal index) have been done for this combustor with the effusion holes in the range of 0.54 % - 1.0 % porosity at M2.2 cruise condition. The results are shown in Figure 13. The result indicated that the amount of cooing air from liner walls and heat shield could be reduced to 12 % in total. The metal liner currently used for the single sector unit has a transpiration-cooling scheme with 18 % cooling air. Hence, if the cooling air is reduced from 18 % to 12 %, the NOx value is expected to go down to about 5EI from 9EI as shown in Figure 12. Based on the temperature distribution in the liners acquired through the thermal paint tests, the hole arrangement for each region is now being optimized.

(3) Further improvement in burners

Several promising options to improve mixing are currently considered for the pilot burner. There are three main modifications in the pilot burners.

Firstly, the shape of swirl vanes will be modified. The current swirl vane of the pilot burner is not parallel to the airflow at the inlet edge. This vane shape may cause a flow separation at the inlet edge of the vanes due to a sharp change in flow angle and therefore the wakes generated at the edge are possible to make mixing worse and induce flashback in the premixed duct. Hence, curved vanes are going to be employed to improve the mixing property.

Secondary, the number of the fuel injection holes is planned to reduce with the same hole diameter for the purpose of increasing the fuel feed pressure. Fuel will have a larger momentum and could even reach the outer region of the premixing duct. This modification is expected to improve mixing property in the entire premixing duct.

Thirdly, an atomizing lip will be removed in the premixing duct. The purpose of this modification is the same as the second modification. By the deletion of the lip, fuel can reach further outer region in the premixing duct and that is expected to have more homogeneous mixing.

FUTURE PLAN

For the sake to achieve the 5EI target at M2.2 cruise conditions, currently the “Dog leg” feed arm, new burners and liner walls with reduced cooling mentioned above are being designed and manufactured for the single sector combustor unit. High-pressure tests will be performed from this April to June at NAL test facility to finalize the specifications of LPP low NOx burners.

Multi sector tests are planned up to 0.6 MPa pressure condition at M2.2 inlet temperature of 915 K at KHI test facility. The tests are planned to start from August 2003 after the burner specifications are determined in the single sector tests. Combustion instability is one of the characteristics of an LPP combustion system that may cause a serious damage to any combustor parts. The multi sector unit has a Helmholtz resonator system to damp the combustion instability in case it happens. The resonator chamber volume is designed to dump the magnitude of instability at a typical possible frequency for this size of this ESPR combustor. The unit also has flashback detection sensors at the main burners to detect the likelihood of flashback especially when the combustor condition is not steady such as light across. The aim of these multi sector tests is to evaluate combustor characteristics that are not able to assess at the single sector unit such as light across, start ignition, temperature traverse and staging. And the second objective is to do a functional check on the resonator system and flashback sensors in advance for the preparation of the high-pressure full annular combustor tests at Rolls Royce. The unit has already been manufactured and the tests will start from early August after the final specification of the burners is determined.

A full annular combustor test is planned in December 2003 in Rolls Royce, Derby plant for the final assessment of the low NOx combustion system. Test specifications and procedure are currently discussed among NAL, KHI and Rolls Royce and the test unit has been being prepared.

ACKNOWLEDGEMENT

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Sample Reference

Shaw, Robert J., et al., 1993, “Engine Technology Challenges for a 21st Century High-Speed Civil Transport,” ISABE93-7064

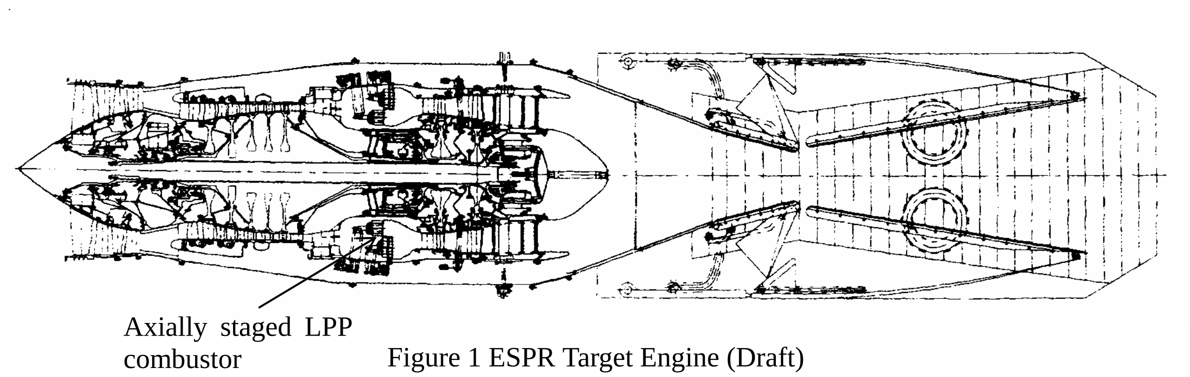


Figure 1 ESPR Target Engine (Draft)

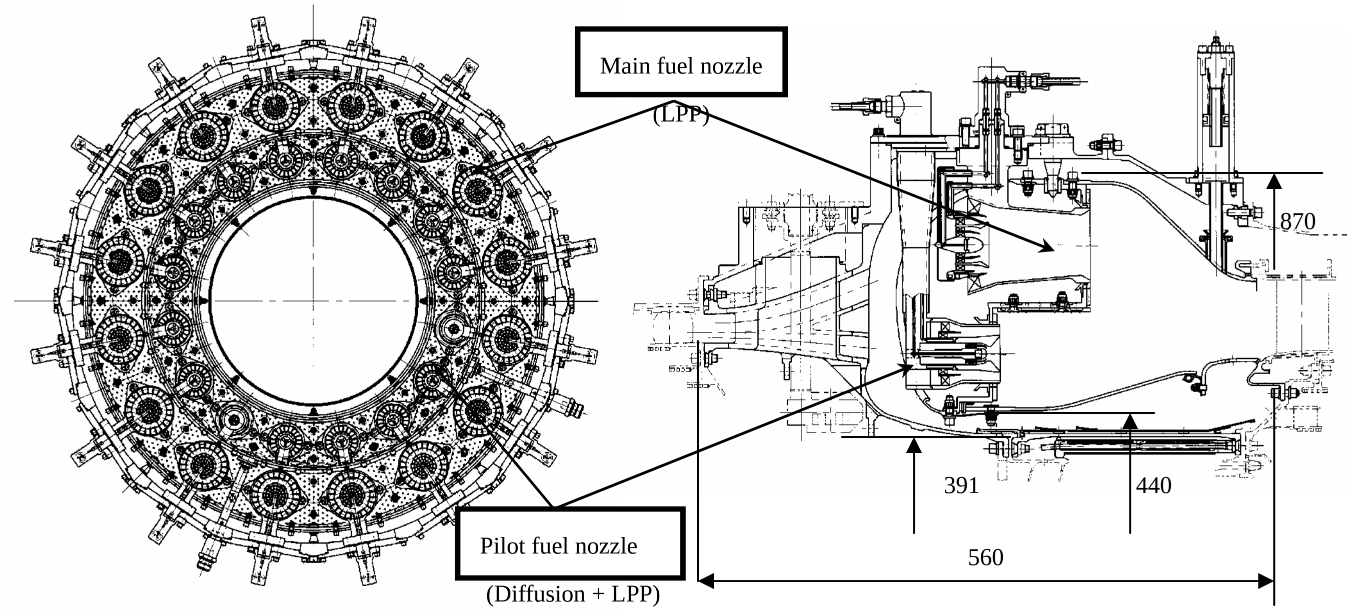


Figure 2 ESPR axially staged combustor

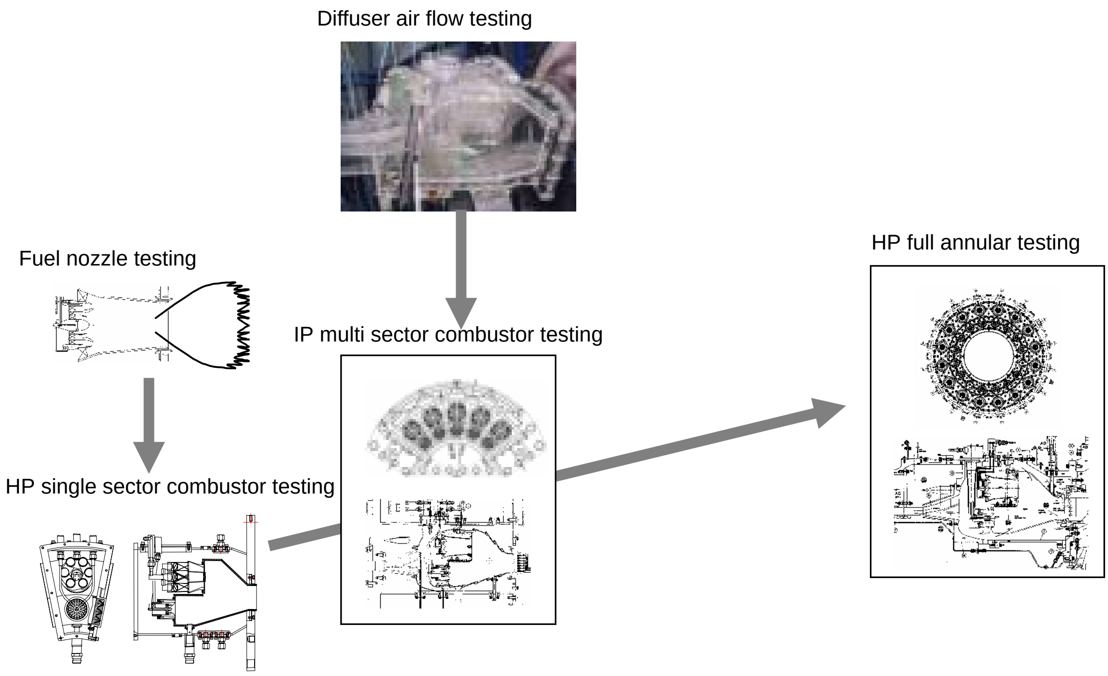


Figure 3 Research & Development plan

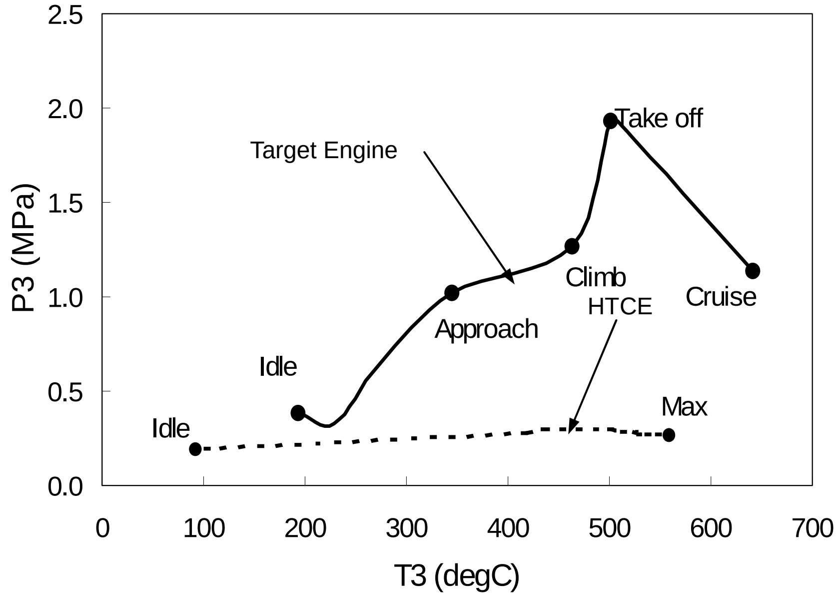
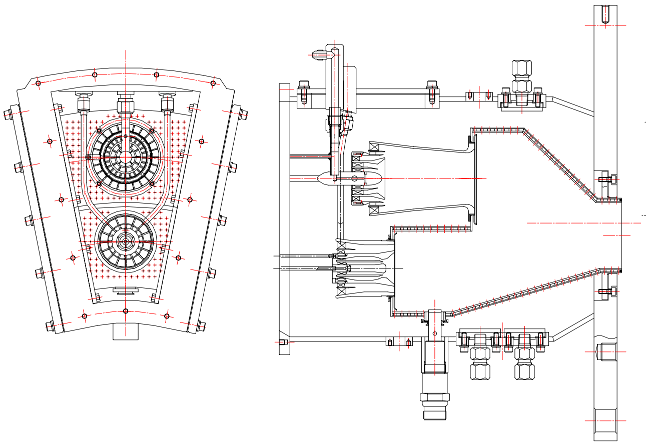


Figure 4 Engine operation conditions



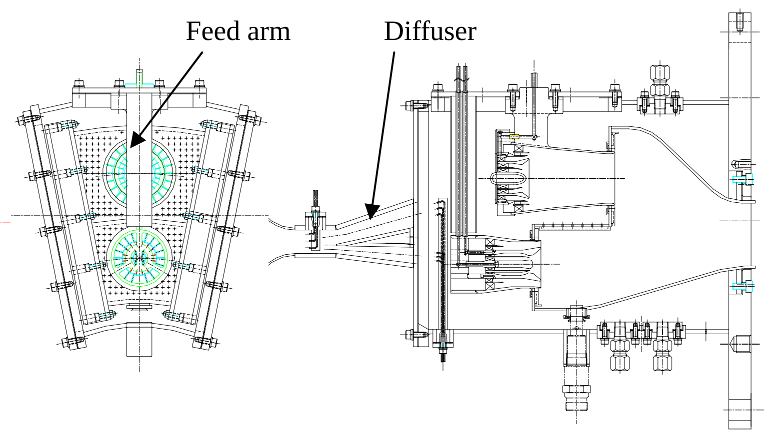


Figure 5 Single sector combustor test unit
(Without diffuser and feed arm)

Figure 6 Single sector combustor test unit

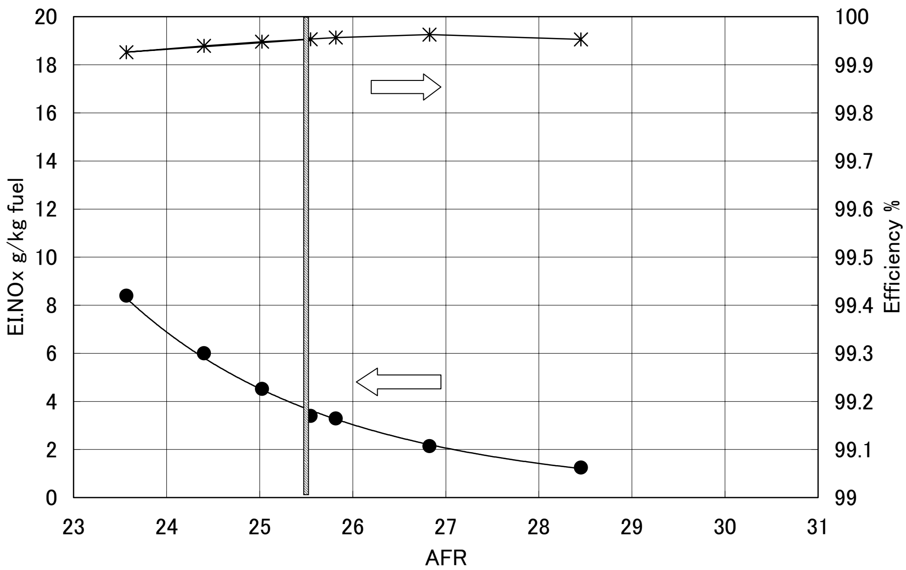


Figure 7 NOx and combustion efficiency

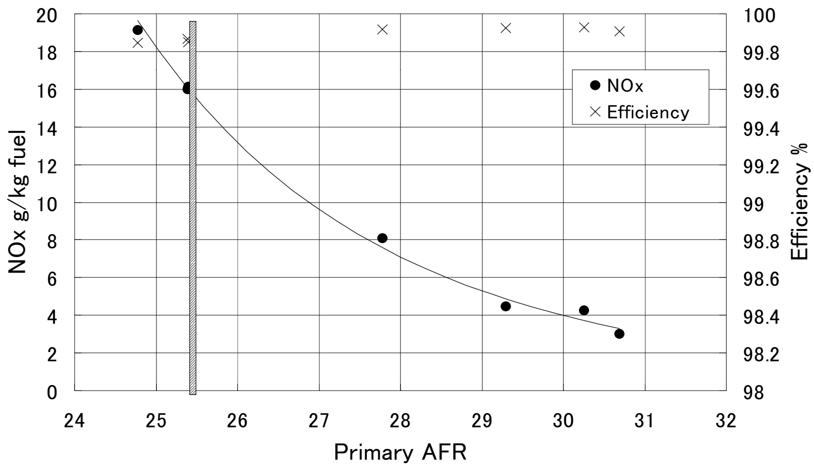


Figure 8 NOx emission and combustion efficiency (engine simulated combustor)

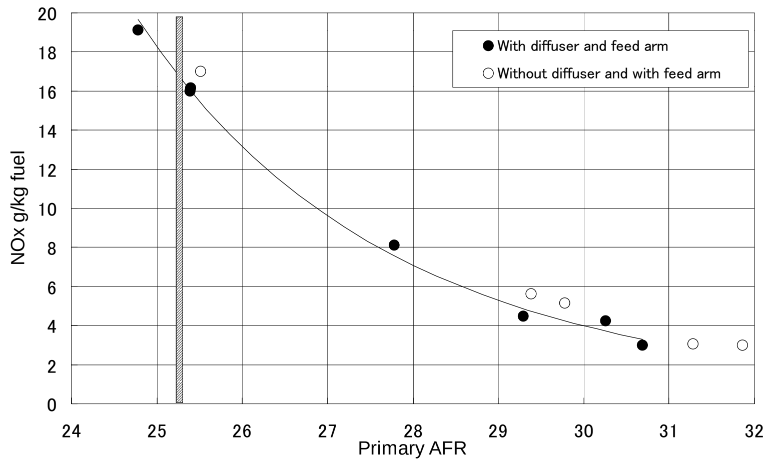


Figure 9 NOx emission comparison between the units with & without diffuser

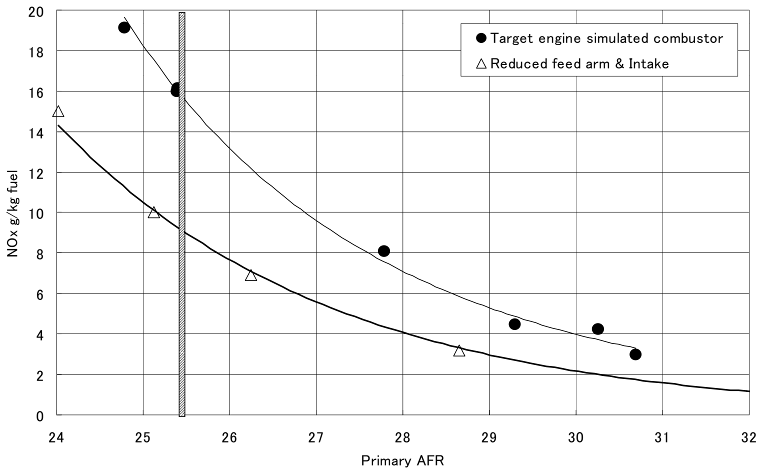


Figure 10 NOx emission comparison between the units with & without feed arm

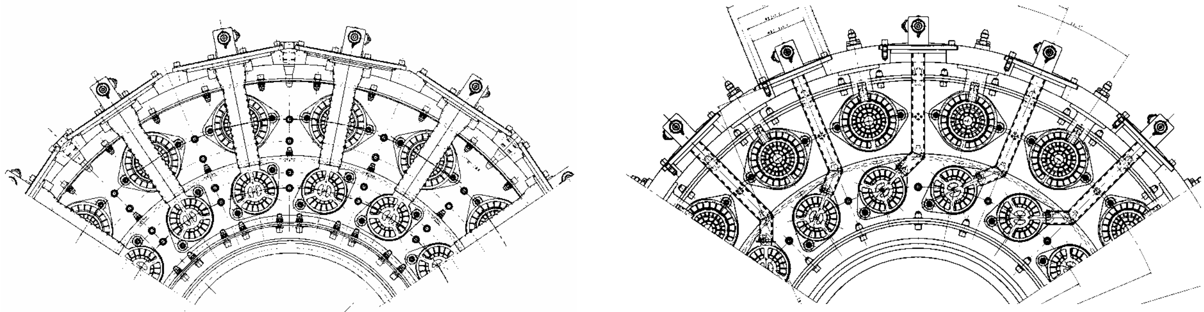


Figure 11 Original feed arm configuration and "Dog leg" feed arm configuration

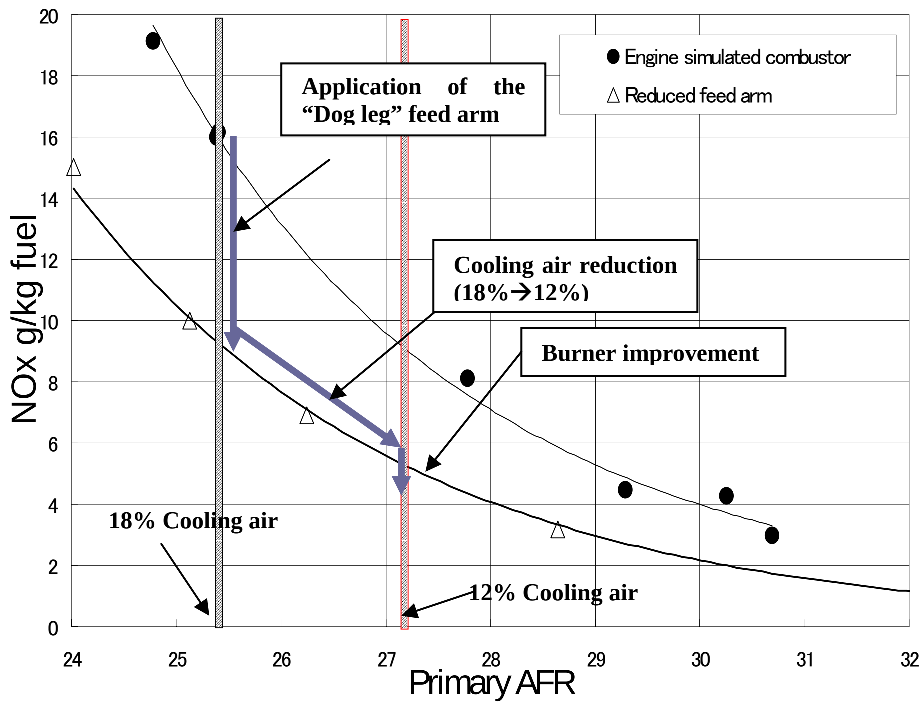


Figure 12 Further NOx reduction plan

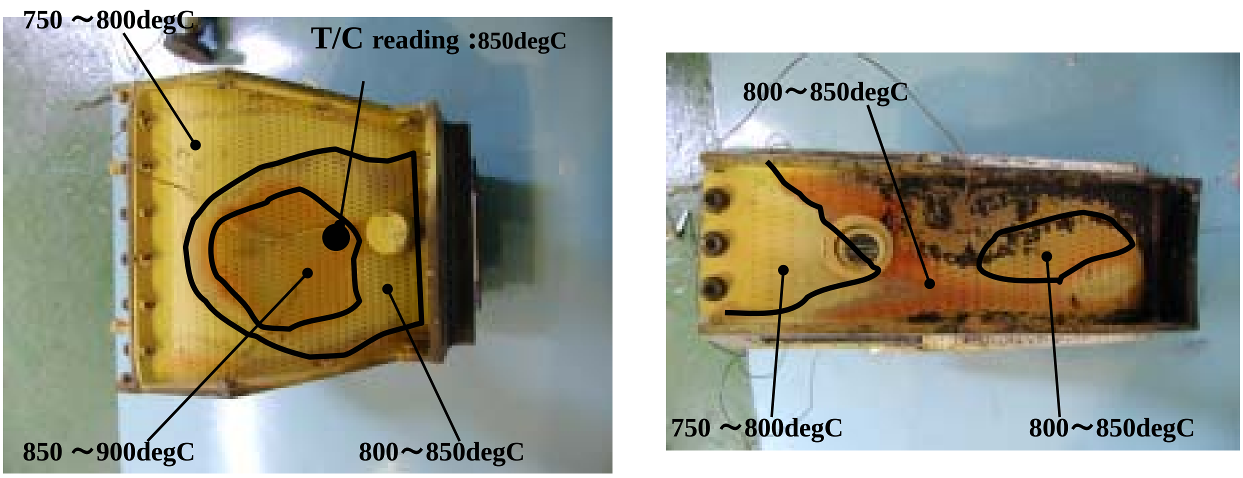


Figure 13 Angled effusion liner thermal paint results