Development Plan of the Next ATREX Engine

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Abstract

This paper describes development status and program of ATREX engine as a propulsion system of future spaceplane. Development activities using ATREX-500 engine from 1990 were finished in 2003 with large number of outcomes. We made system-level validation of the hydrogen fuel turbojet engine with air precooling device under sea level static condition. As a next step, we started design of the flight-type ATREX engine with large thrust and lightweight.

1. Background

Japan Aerospace Exploration Agency (JAXA)

On October 1, 2003, ISAS, NAL and NASDA were merged into one institution: the Japan Aerospace Exploration Agency (JAXA). Aim of this consolidation is to make more efficient researches and developments by a concentration of Japanese aerospace technologies.

Most of researchers on hypersonic air-breathing engines were concentrated in Institute of Space Technology and Aeronautics (ISTA), which is former NAL, on the consolidation. The Future Space Transportation Research Center in ISTA is in charge of researches on reusable rocket engines and Turbine Based Combined Cycle (TBCC) engines, whereas Rocket Based Combined Cycle (RBCC) engines are mainly studied in Kakuda Propulsion Laboratory. R&D of the ATREX engine, which was conducted in ISAS before the consolidation, is going in ISTA now.

2. Japanese R&D activities on TBCC engine

Researches on the ATREX-500 engine

The ATREX engine is an air turbo ramjet engine working in expander cycle. Development study of this engine initiated in 1986 with the analytical work phase and then moved to the experimental verification phase with the scaled ATREX engine (ATREX-500) with 300 mm of fan inlet diameter since 1990 [1]. It has been tested under sea level static conditions. Since 1995 the regenelatively cooled combustor and the air precooler were additionally integrated in ATREX-500. The most distinctive feature of the ATREX engine is an air precooling system as shown in Fig.1. This is a device for protecting turbo-machinery from aerodynamic heating under hypersonic flight conditions. Moreover, the specific power and thermal efficiency of Brayton cycle engines can be improved significantly by precooling the incoming atmospheric air. Liquid hydrogen is used as fuel and working fluid of turbines. ATREX produces the effective thrust from sea level static up to Mach 6 at the altitude of approximately 30 km.

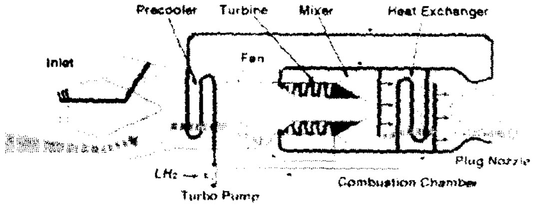


Fig.1 Flow Diagram of the ATREX Engine

Number of 67 firing tests with cumulative duration of 3,900 seconds has been conducted at Noshiro Testing Center in ISAS with ATREX-500 [2]. A photo of firing test is shown in Fig. 2. With this engine, we made system-level verification of advanced technologies for hypersonic propulsion; e.g. air-turbo-ramjet, liquid hydrogen fuel combustion, expander cycle, regeneratively cooled combustion chamber, inner heat exchanger, pre-cooling system, and methanol injection system for preventing frost formation [3].

Fig.2 The ATREX Engine at Noshiro Testing Center

Researches on Inlets and Nozzles

Variable geometry supersonic inlets have been studied experimentally in the wind tunnel since 1992 as well as the analytical study with CFD [4), 5)]. The inlet test models are shown in Fig.3. Inlet performance attributes, such as total pressure recovery, mass capture ratio, and external drag, were investigated with a number of wind tunnel tests and CFD simulations. Not only static performance tests, but also inlet control tests were carried out to establish the control architecture for restarting the inlet during the hypersonic flight. Thrust efficiency and boat tail drag of the axisymmetric plug nozzles and rectangular type nozzles were investigated experimentally 6).

Researches on High Temperature Elements and Materials

The trial manufacture of advanced carbon/carbon (ACC) composites and CMC composites has been conducted to apply for the critical hot structures; e.g. combustor, nozzle, and inlet 7) 8) 9). The test pieces are shown in Fig.4.

(1) Axisymmetric Inlet (2) Axisymmetric Nozzle

(3) Rectangular-type Inlet (4) Rectangular-type Nozzle

Fig.3 Wind Tunnel Test Models (1: Axisymmetric Type Inlet, 2: Axisymmetric Type Nozzle, 3: Rectangular Type Inlet, 4: Rectangular Type Nozzle)

(1) Combustor (2) Turbine Ring

(3) Nozzle Centerbody (4) Inlet Leading Edge

Fig.4 Trial pieces of composites (1: ACC Combustor, 2: ACC Turbine-Ring, 3: ACC Nozzle Centerbody, 4: CMC Inlet Leading Edge)

3. Program for the Next ATREX Engine

For next flight demonstration tests, we are making system analysis of two different size engines: full-scale engine and sub-scale engine. Basic design of the full-scale engine is difficult unless verification of the sub-scale engines is completed. However, in order to define specifications of the sub-scale demonstration engine, conceptual design studies of the full-scale engine for practical use is indispensable. Therefore studies on these engines must be performed in parallel.

Table 1. Specifications of Two Engines (Plan)

	Fan Tip Diameter [m]	Total Length [m]	Weight [kg] Requirement	Thrust [Mgf] Requirement
Full-scale Engine	1.2	16	5900	20
Sub-scale Engine(M-size)	0.3	4.4	310	1.0
Sub-scale Engine(S-size)	0.1	1.5	40	0.1

Full-scale Engine Analysis

Target of our researches is to develop a TSTO spaceplane powered by several number of ATREX engines as shown in Fig.5. This spaceplane consists of two vehicles: 1st stage booster and 2nd stage orbiter. Gross Take-Off Weight (GTOW) is 270 Mg (1st stage: 140 Mg, 2nd stage: 130 Mg). 3 Mg of payload can be transported into LEO by a fully reusable orbiter. As for the case of using an expendable orbiter, it is possible to put 10 Mg payload into the orbit. Take-off thrust and thrust-to-weight ratio of the ATREX engine reaches 20 Mgf and 3.0 respectively. Specific impulse is more than 3,500 sec under sea level condition. For accelerating the vehicles up to Mach 6, this engine has the air precooling system cooling down air upstream of the compressor. The maximum velocity of the conventional turbojet engines without this system is lower than Mach 4 not to make incoming air temperature exceed critical value of the compressor. By increasing staging velocity from Mach 4 to Mach 6, fuel consumption of the orbiter can be reduced by 5 %.

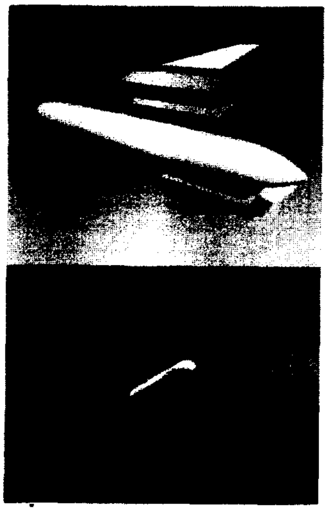


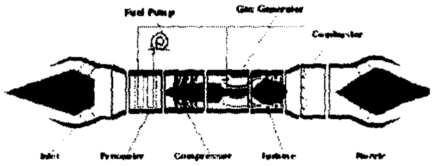
Fig.5 Conceptual View of the TSTO Spaceplane (Upper: Rectangular Type Engines, Lower: Circular Type Engines)

Rectangular type inlets or circular type inlets are installed on the under surface of a delta wing as shown in Fig.5. Rectangular type inlets are considered to be heavier than circular type inlets, however, rectangular type inlets may have good performance especially under hypersonic flight conditions.

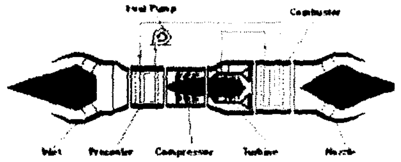
Engine Cycle Optimization

We started Multi-Disciplinary Optimization (MDO) of the TSTO spaceplane powered by TBCC engines from 2000 [10) 11) 12)]. Objective of this study is to make decision on the basic specification of the next flight-type engine. Among TBCC engines, there were several promising candidates; e.g., expander ATR engine, precooled turbojet engine, gas-generator ATR engine, and turbo-ramjet engine. Flow diagrams of these candidates are shown in Fig.6. The expander ATR engine drives both of a main-turbine and a FTP turbine with gaseous propellant instead of combustion gas, whereas the precooled turbojet engine drives only the FTP turbine with propellant. The precooled turbojet engine has a partial expander cycle. The gas-generator ATR drives turbines with combustion gas of propellant and oxidizer in the gas-generator. The turbo-ramjet engine has a ram-duct surrounding the turbojet engine. This engine is mechanically transformed from turbojet-mode to ramjet-mode at Mach 3 or 4.

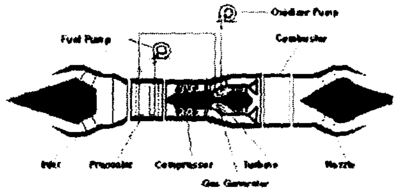
(1) Precooled Turbojet



(2) Precooled Expander ATR



(3) Precooled Gas Generator ATR



(4) Turboramjet

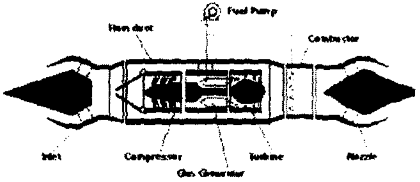


Fig.6 Flow Diagrams of TBCC Engines

In order to make quantitative comparison among these candidates, we developed a MDO program for the TBCC engines. We combined engine simulation program with other tools as shown in Fig.7. This program includes a propulsive performance model, a vehicle aerodynamics model, a structure mass model, a flight simulator, and an optimizer. As the optimizer, we adopted Real-coded Genetic Algorithm (GA) in order to optimize discrete variables; e.g., compressor stage number and turbine stage number, which are significant designs for TBCC engines. Design variables of Engine, Airframe, and Trajectory were optimized for minimizing GTOW as an evaluating function.

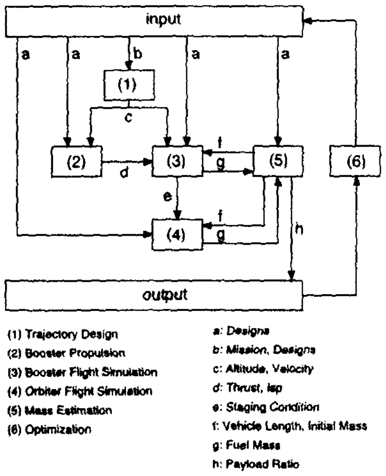


Fig.7 The MDO Program for the TBCC Engine Design

As a result of this study, it was concluded that the precooled turbojet engine was the most promising among TBCC engines. The specific impulse comparison of the TBCC engines is shown in Fig.8. From this figure it is found that the precooled turbojet is superior to all other engines in low-speed conditions. The turbo-ramjet engine shows good performance in high-speed conditions. However, this engine has a weight penalty due to the heavy ram-duct and a mode-switch valve. Therefore, the precooled turbojet was the best in total performance when it is installed on the TSTO spaceplane.

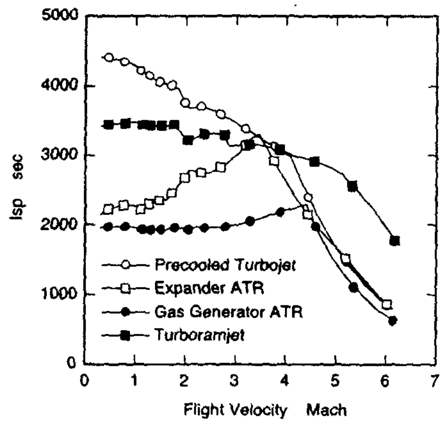


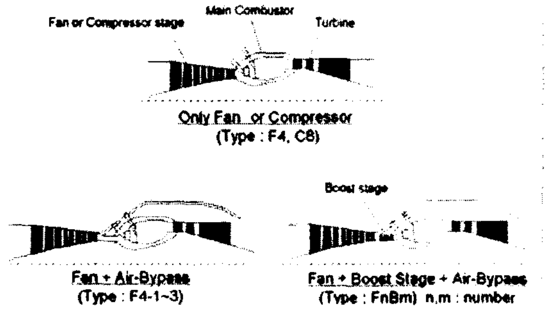
Fig.8 Specific Impulse of the TBCC Engines

The expander ATR shows relatively low specific impulse, due to temperature constraints on heat exchangers. The coolant temperature, which is equal to Turbine Inlet Temperature (TIT) of the ATR engine, was 1200 K in the Full-scale engine analysis. In case that TIT is 1500 K or higher by applying advanced materials to heat exchanger tubes, it is possible for the expander ATR to match up to other engines in specific impulse.

From above described studies, we selected the precooled turbojet as a next development engine for flight demonstration.

Optimal Design of the Turbo-machinery

In 2003 we made a conceptual study on the turbo-machinery in detail [13]. The purpose of this study was to define the configuration of the engine core. Effects of fan stage number, turbine stage number, boost stage number, and bypass ratio on thrust performance were investigated. Configurations compared in this study are shown in Fig.9.



CASE No.	F4	C8	F4-1	F4-2	F4-3	F4B2	F4B3	F4B4	F3B4	F2B4	F2B7
Fan/Compressor Stage No.	4	8	4	4	4	4	4	4	3	2	2
Boost Fan Stage No.	0	0	0	0	0	2	3	4	4	4	7
Turbine Stage No.	2	2	2	2	2	2	2	2	2	2	2
Bypass Ratio	0.00	0.00	0.11	0.25	0.43	0.43	0.43	0.43	0.43	0.43	0.43
Design Pressure Ratio (Fan/Compressor)	6.2	16.3	6.2	6.2	6.2	6.2	6.2	6.2	3.9	2.5	2.5
Design Pressure Ratio (Boost Fan)	-	-	-	-	-	10.6	12.0	15.4	9.7	6.1	10.3
Design Air Flow Rate (kg/s)	177	177	177	177	177	177	177	177	177	177	177
Design Fan/Compressor Efficiency	85.4	80.7	85.4	85.4	85.4	81.5	81.5	81.5	81.5	81.5	81.5

Fig.9 Basic Configuration of Engine Core

We evaluated effects of the air bypass ratio on thrust performances. We also studied applicability of boost fan stages and a multi-stage compressor. For the engine cycle calculation, the performance curve of fan, turbine and so on were assumed based on IHI jet engine database.

Fig.10 shows the calculation result of thrust performances against Mach number in each configuration. F2B7 has the highest performance within the range of operating Mach number, whereas C8 has the lower performance in middle Mach number due to the limitation of fan tip speed and more attractive in low Mach number.

Fig.11 shows mass fraction of subsystems excluding propulsion (engines, propellant and tanks), which shows payload capability of the spaceplane. The comparative results indicate that the F2B8 is the most attractive.

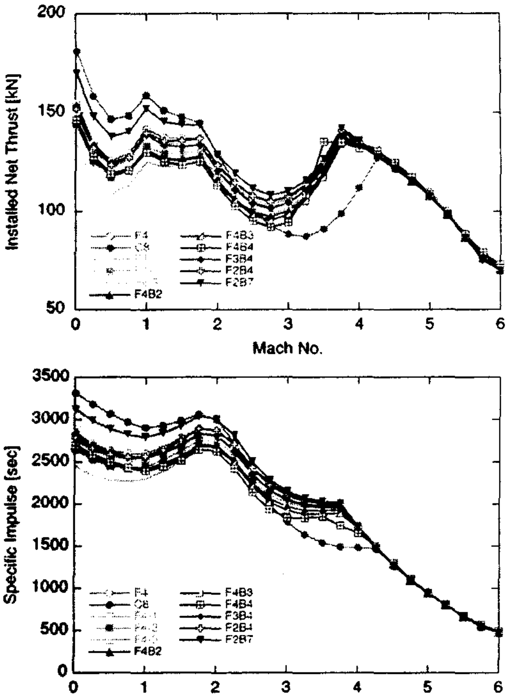


Fig.10 Thrust Performances Comparison

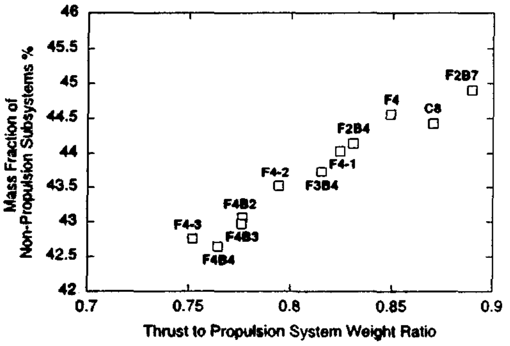


Fig.11 Payload Capability of the TSTO Spaceplane

In addition to the performance quantitative comparison, we also compared qualitative indices; e.g. mechanical reliability and development risk. F4-3 is attractive because of its reliability owing to structural simplicity. F4 has the simplest configuration, however, it is not applicable by weak structural strength due to small hub ratio of the turbine. In addition, pressure drop at the fan outlet also increases by high velocity of axial flow.

Based on the foregoing results of calculation, we selected F4-3, and F2B7 for further comparative studies. It is necessary to continue the more detailed trade-off analysis to select the best configuration.

Fig.12 shows the cross-sectional drawing of the engine drawn based on the selected compressor configuration. It is designed that the 4-stage fan is used for the compressor and IGV (Inlet Guide Vane) is installed in front of the 1st fan to escape from the stall in off-design operation. VSV (Variable Stator Vane) is also installed at fan outlet to control the amount of bypass-air flow rate. An annular type, which is successfully proved its performance in hydrogen combustion, is selected for main combustor, and a spray bar type for the afterburner, based on experience in the jet engine development. Liquid hydrogen cools three bearings, the turbine disk and the afterburner casing. Fig.13 shows materials used for each component. Nickel based heat resistant alloy for basic materials and titanium alloy for the fan are selected.

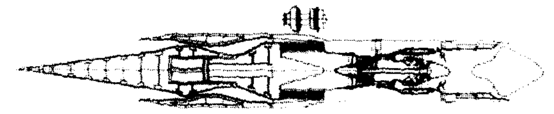


Fig.12 The Full-scale Engine Schematic

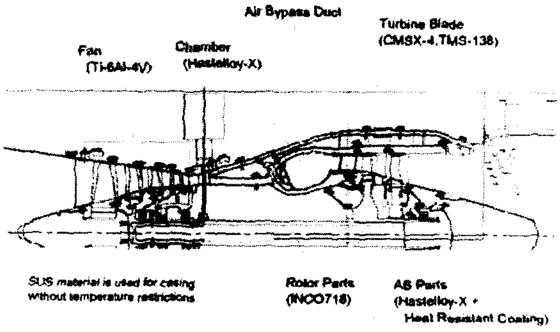


Fig.13 Material for the Core Engine

In 2004, our MDO program for the full-scale engine analysis is to be merged into a larger and more comprehensive program, which is under development in JAXA. This program can deal with not only the TSTO spaceplane with air-breathing engine, but also rocket spaceplanes, RBCC spaceplanes, and Expendable Launch Vehicles (ELV).

Sub-scale Engine Analysis

We have designed two sub-scale engines for near-term flight demonstration tests, M-size engine and S-size engine.

The M-size engine is a prototype engine for middle-scale flight demonstration. Fan tip diameter of this engine is 0.3m, which is equal to that of the ATREX-500. This is to reduce development cost by utilizing existing test facilities. Conceptual view of a testing vehicle called Engine Flight Test Bed (EFTB) is shown in Fig.14. This vehicle consists of 2 stages. The first stage is a solid booster accelerating up to Mach 2.0. The ATREX engine is installed on undersurface of the second stage. Because this vehicle is accelerated with the tested engine, accidents in the engine shall cause loss of vehicle. Therefore, not performance oriented design but reliability oriented design must be adopted for the M-size engine. For increasing reliability and reducing development risks, this engine is designed with much of safety margin and the present and near-term technologies. Conventional materials are mainly applied. Advanced composite materials are used only in limited static items; e.g. cowl lip, spike tip, and some casings.

S-size engine will be tested being installed on a small solid booster or a rocket based RLV testing vehicle. Vehicle has a main engine for acceleration. Therefore, there is little possibility that tested engine becomes a factor of loss of vehicle. Therefore, this engine can adopt highly advanced technologies and materials. Figure 15 shows cross-sectional view of the S-size engine. Firing tests in a hypersonic wind tunnel for this engine are planned in a few years [14].

Fig.16 shows a development schedule of the sub-scale engine. It may take 6 years and 8 years to develop the engine and complete flight verification test respectively. Firstly, various rig tests will be planned for main components of the engine and next the test of system level. It is our plan that demonstration data are to be collected through ground tests and then the flight verification test will be conducted to collect data for further developmental steps.

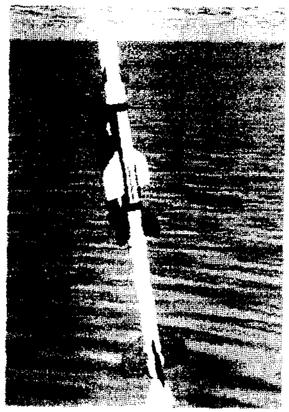


Fig.14 Conceptual View of the EFTB

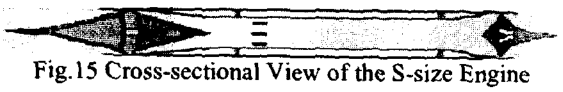


Fig.15 Cross-sectional View of the S-size Engine

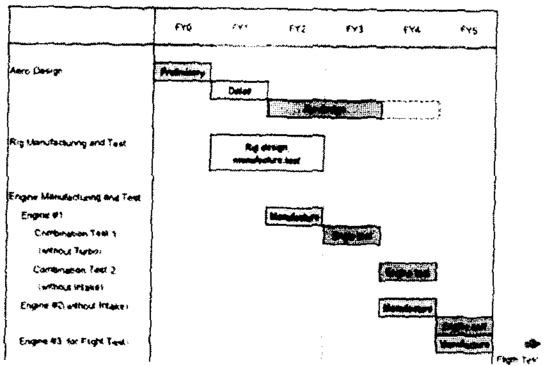


Fig.16 Development Plan for the Sub-scale Engine
(not authorized)

Conclusion

Japanese R&D activities on TBCC engine from 1986 to 2003 and near-term plans were described in this paper. We made system-level validation of the TBCC engine under sea level static condition with the ATREX-500 engine. Technologies on supersonic inlets, nozzles, and advanced materials were also cumulated. As a next step, we started design of the flight-type engine with large thrust and lightweight. In order to make trade-off analysis on the full-scale engine for practical use, we developed a MDO program including a propulsive performance model, a vehicle aerodynamics model, a structure mass model, a flight simulator, and an optimizer. We selected the precooled turbojet as a next development engine. Anticipatory flight demonstration plans using sub-scale engines were also introduced in this paper.

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