Development of the LE-X Engine

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The expander bleed cycle is an engine cycle that was developed in Japan for practical applications. It has robust operational characteristics against disturbances due to its simplicity, and was adopted for the LE-5B engine, the second-stage engine of H-IIA launch vehicle. The LE-5B has many capabilities, providing restart capability, throttling and idle mode combustion (extremely low thrust operations) capability, these capabilities is evaluated highly in the world due to its reliable performance. The expander bleed cycle was first adapted for the LE-5A engine, which was an improved version of the LE-5 engine. The LE-5 was the first Japanese liquid oxidant/hydrogen (LOX/LH2) engine. This cycle was also adapted for the LE-5B engine, and more recently, for the MB-XX engine, which is a cooperative development between Mitsubishi Heavy Industries, Ltd. (MHI) and U.S. Pratt and Whitney Rocketdyne. These are all second-stage engines. Now, MHI is adopting this cycle for the first-stage engine of a next-generation launch vehicle under contract with the Japan Aerospace Exploration Agency (JAXA), with the intention of providing world-standard first-class reliability. This report describes the features of the expander bleed engine cycle and our approach for providing the highly reliable LE-X engine.

1. Introduction

In 1999, H-II Launch Vehicle Flight No. 8 ended in failure due to an explosion in the first-stage LE-7 engine during flight. For the cryogenic propellant engine, the pump had to be cooled sufficiently by the propellant. The propellant had to be pressurized to the required pressure for the fuel supply to avoid pump suction failure and ensure stabilized combustion acceleration when starting. However, during Flight No. 8, the second-stage vehicle, in which the LE-5B was installed, was disconnected from the first-stage vehicle in an unstable tumbling condition, so that the engine started with insufficient cooling and tank pressure. However, under such conditions, the LE-5B engine started normally and provided stable and rated operation until it received a destruction command (**Figure 1**). This resulted in an unexpected verification of the robust characteristics and reliability of the expander bleed cycle (EBC), which was developed in Japan for practical use and later adopted for the LE-5B engine.

This engine cycle has the potential to be adapted for human space-flight engine, and also has the potential to be cost competitive due to their simple systems. A previous study verified the adaptability of the EBC for large-thrust first-stage engines. We are currently developing an LE-X first-stage engine for next-generation launch vehicles, adopting this engine cycle with the aim to develop world-standard first-class reliability.

This report describes the features of the EBC developed in Japan, its developmental history, and the present activities used to obtain high reliability for the LE-X engine.

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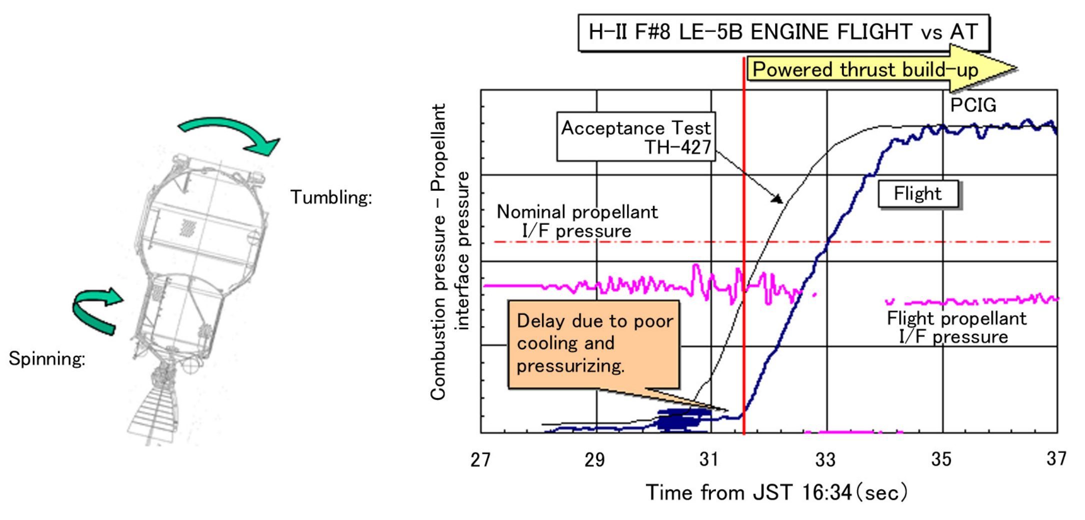

Figure 1 Second-stage engine used in the H-IIB, starting from Flight No. 8

2. Development of the EBC engine

2.1 Liquid-Fuel Rocket Engine Cycles

In a rocket engine cycle, the propellant is pressurized by a turbopump and combusted in a combustor to produce the thrust force. The engine cycle is categorized according to the driving method of the turbopump turbine (**Figure 2**).

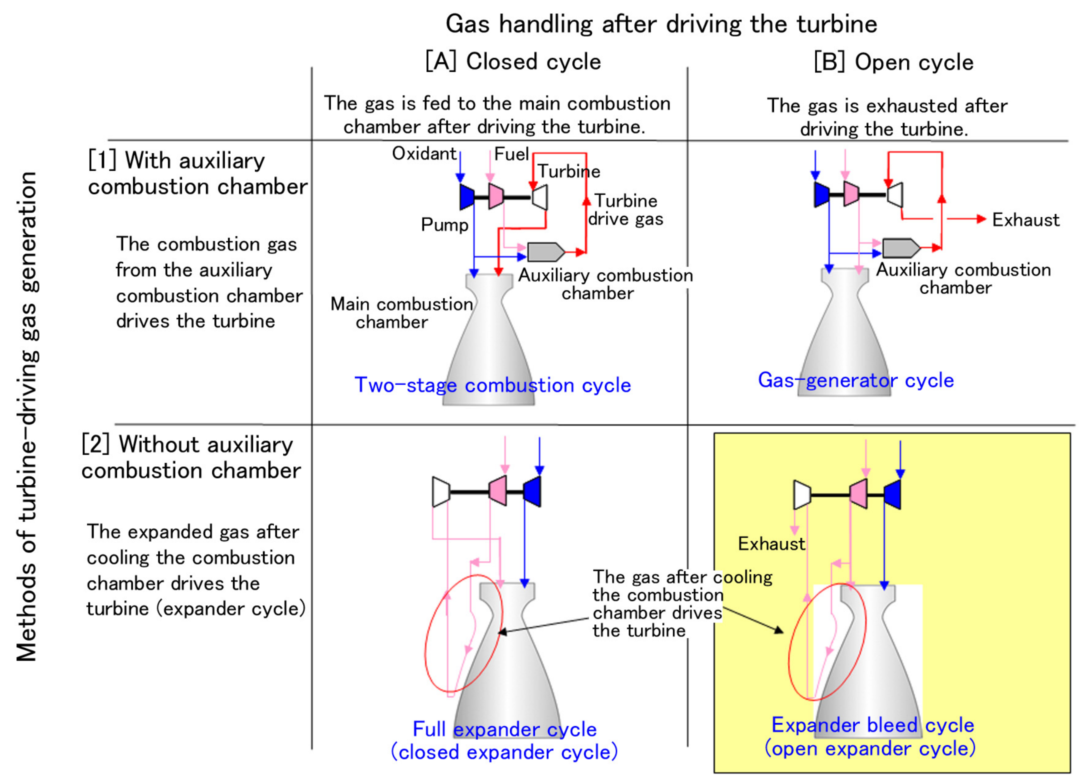

Figure 2 Engine cycles

The categories based on how the gas is handled after driving the turbine are as follows:

- Closed cycle – the gas is returned to the main combustion chamber and combusted [A];
- Open cycle – the gas is exhausted [B].

There are also categories based on turbine gas-generation method, as follows:

- The gas is generated in an auxiliary chamber [1]);
- The turbine is driven by a high-temperature propellant after cooling the combustor [2].

These categories are referred to as the two-stage combustion cycle ([A]-[1]), the gas-generator cycle ([B]-[1]), the full expander cycle ([A]-[2]), and the EBC ([B]-[2]), respectively.

The features of each engine cycle are described below.

(1) Performance

An open cycle rejects the turbine-driving gas. However, in a closed cycle, after driving the turbine, the gas is combusted in the main combustion chamber for utilization as thrust power. This gives a high specific impulse (I_{sp}) value (thrust force divided by propellant weight per unit time), providing superior performance.

(2) Simplicity

The expander cycle does not have an auxiliary combustion chamber and has a simple construction.

(3) Controllability on starting

In a system where the turbine-driving gas is generated in the auxiliary combustion chamber, controlling the start timing of each chamber is complicated because the auxiliary and main chambers are separate. The timing is further complicated in a closed cycle, because the main chamber is downstream of the turbine, so that the exhaust pressure of the turbine is increased by the pressure increase in the main combustion chamber upon ignition, which affects pump operation. However, in the EBC, the timings of combustion chamber pressure increase and turbine power increase are coupled, because the gas that cools the main chamber is used as the turbine-driving gas and then rejected. The turbine backpressure is immune to combustion pressure, and the engine starts in an autonomously controlled manner.

(4) Safety

In a system where the turbine-driving gas is generated in an auxiliary combustion chamber, the adjustment of the oxidant and fuel flow rate (mixing rate) controls the turbine-driving gas temperature. In other words, if the controlled mixing rate is changed by some abnormality, such as a valve malfunction, the temperature of the turbine-driving gas can increase up to a maximum of 3,500 K. This may cause catastrophic destruction. In contrast, in the EBC, the gas that cools the combustion chamber is used to drive the turbine. A change in the mixing rate in the combustion chamber has little effect on turbine gas temperature. This is an inherently safe cycle (**Figure 3**).

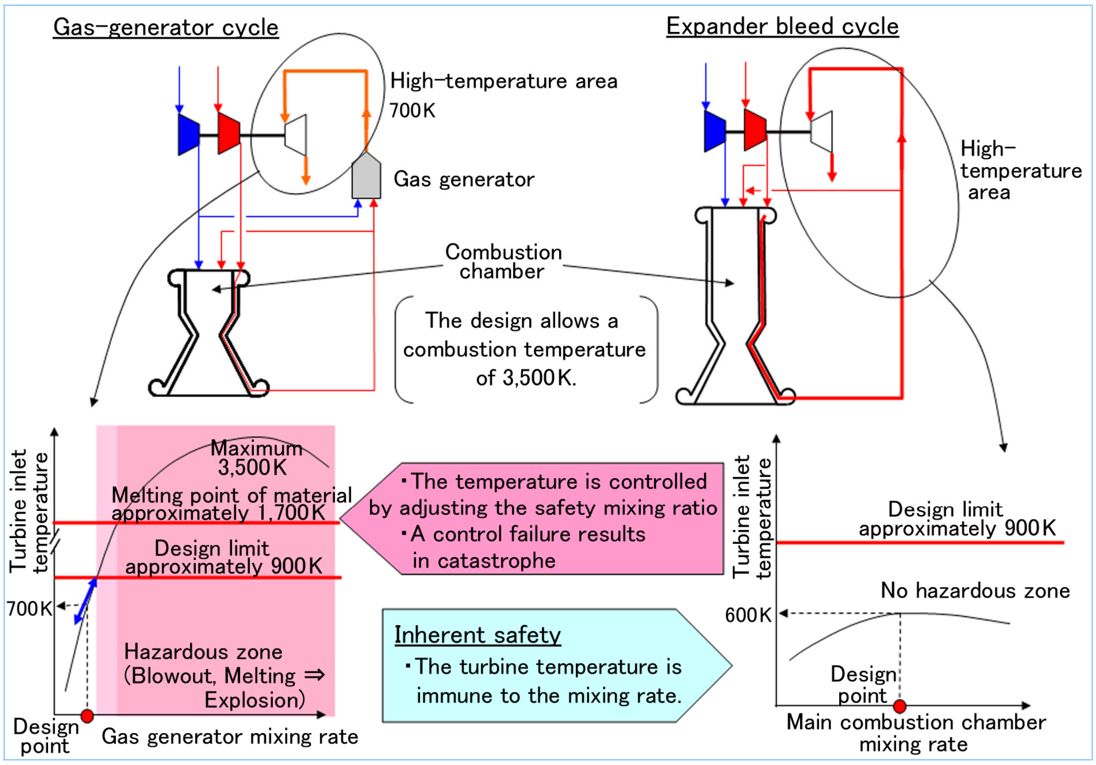

Figure 3 Comparison of turbine-driving gas

(5) Increased engine thrust

In a system where the turbine-driving gas is generated in an auxiliary combustion chamber, the engine thrust is controlled by the auxiliary chamber power, and the thrust power can be increased simply by increasing the combustion gas flow in the auxiliary chamber. In the EBC, thrust can be increased up to approximately 200 tons by enlarging the combustion chamber and absorbing the heat required to drive the turbine. Because the turbine-driving gas is returned to the combustion chamber in the full expander cycle, the pump discharge pressure rises and the combustion chamber becomes too large to absorb the heat from the turbine-driving force.

Thus, based on these characteristics, the EBC is a simple, autonomously controlled, inherently safe engine that can provide large thrust increases.

2.2 Development of a Two-Stage Engine

Figure 4 shows the history of the expander bleed engine. The world’s first practical engine using the EBC was the LE-5A used in the second stage of the H-II launch vehicle. The potential of this engine had been discovered during the development stage of the LE-5, the predecessor of the LE-5A.

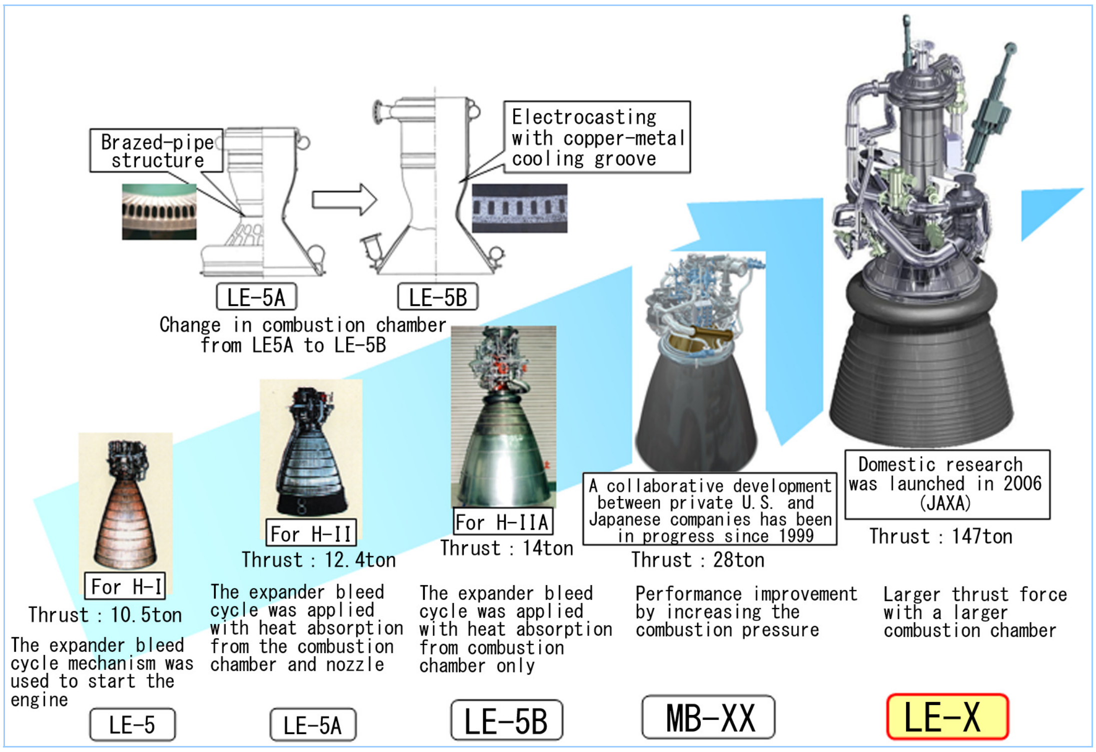

Figure 4 Developmental history of expander bleed engines

(1) LE-5 engine

The LE-5 engine was the first Japanese LH2/LOX propellant rocket engine. The gas-generator cycle was adopted for the engine cycle. In this cycle, the system transition to the gas-generator cycle is completed after increasing the engine power to some extent and operating the auxiliary combustion chamber. The J-2 (the third-stage engine in the Saturn launch vehicle) and RS-68 (the first stage in the Delta IV) engines, which had the same cycle, used a starter (high-pressure starting tank or an explosive type). In the LE-5, the starter was omitted for simplification, and hydrogen gas that cooled the combustion chamber drove the turbine. During transition to the rated operation, the auxiliary chamber started after the main combustion chamber power rose with the turbine power to some extent. In other words, the EBC was used to start the engine, and later, the system was transferred to a gas-generator cycle. This was the first attempt in the world to adopt an EBC to start a gas-generator cycle.

In the early stages of development, the engine took a considerable amount of time to establish the starting sequence from the EBC to the gas generator operation. A preliminary combustion test was performed using the EBC without the gas generator to verify the durability of the combustion chamber. The heat absorbed in the brazed-tube combustion chamber adopted in the LE-5 was not sufficient to drive the turbine, and the thrust and performance (I_{SP}) were not satisfactory, however, this was the first step leading to the advent of the EBC engine, a proprietary system invented in Japan.

(2) LE-5A engine

Study of the expander bleed operation in the LE-5 engine demonstrated that a sufficient amount of heat absorption could provide the required thrust power and performance. Thus, development of the LE-5A engine was started. In the LE-5A, the heat was absorbed through the brazed-tube combustion chamber and the nozzle cooling skirt. The high-temperature hydrogen gas drove the turbine to provide the required rated thrust and performance.

(3) LE-5B engine

In the LE-5B engine, the design was revised from a brazed-tube combustion chamber to an electroformed combustion chamber with copper-alloy cooling grooves. The new system provided enough heat absorption only from the combustion chamber to drive the turbine. In this process, the engine system was simplified and could be tested without the nozzle skirt. Therefore, engine combustion experiments could be performed not only in a high-vacuum testing facility with the nozzle skirt installed, but also at atmospheric pressure without the nozzle skirt, and the development cost could be drastically reduced. The brazed-tube combustion chamber was abolished, and simplification of the nozzle structure reduced the engine cost.

In addition to 100% rated operation, throttling tests at 60%, 30%, and at extremely low levels (3%) for idle-mode operation only using the tank-head pressure without operating the turbine were demonstrated and verified the stable operating capability over a wide range of conditions.

(4) MB-XX Engine

Rocket engines provide thrust by accelerating supersonic-velocity combustion gas with a divergent nozzle. A larger expansion ratio (the ratio of the nozzle outlet area to the throat area) can result in better performance (I_{SP}). The EBC has an inferior I_{SP} compared to two-stage combustion or full expander cycles. Thus, development of the MB-XX engine was started to improve the performance using a higher expansion ratio by increasing the combustion pressure and reducing the throat area. In the MB-XX engine, the combustion pressure was raised from 3.6 MPa, used in the LE-5B, to 14 MPa, and I_{SP} was improved. This engine development is a private collaborative project between Mitsubishi Heavy Industries, Ltd. (MHI) and U.S. Pratt and Whitney Rocketdyne (PWR). The hot firing tests at the Tashiro field laboratory in 2005, assembling the LH2 turbopump (FTP) made by PWR and the combustion system and LOX turbopump (OTP) made by MHI, were demonstrated the required thrust/performance (**Figure 5**).

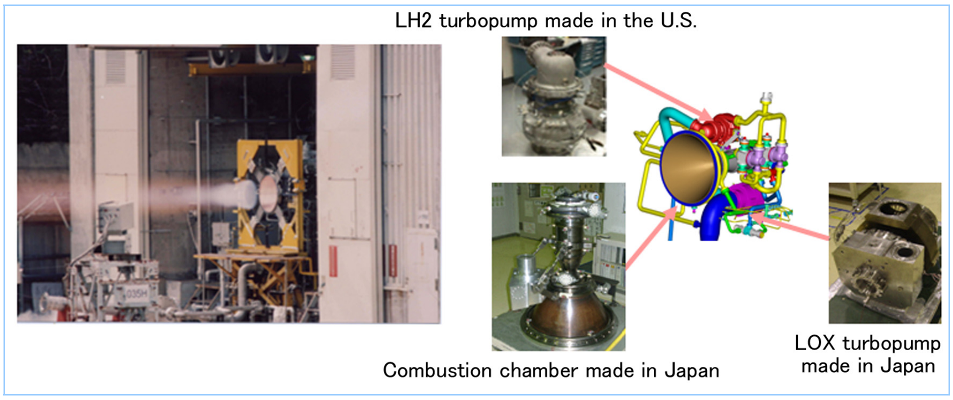

Figure 5 MB-XX engine system demonstration

3. Approach to Obtain High Reliability

The rocket engine is the most fragile component in a launch vehicle because of its severe heat, pressure, and vibration environment. The approach used to develop the first-stage LE-X engine for next-generation main launch vehicles attempts to improve the reliability by several orders of magnitude through the followings:

- Adoption of an engine cycle resilient against failure.

  The EBC will be used for the first-stage engine to increase thrust;

- Reliability perfection during the design stage.

  As shown in **Figure 6**, valve problems have frequently occurred, even during mass-production phase of H-IIA launch vehicles. A quality-improvement program based on intensive production management (SV100 Tactics) and design-reliability improvement program (Valve Task Force) were applied to solve the problems, and led to a drastic reduction of defects. These procedures will be applied to the development of the entire LE-X engine.

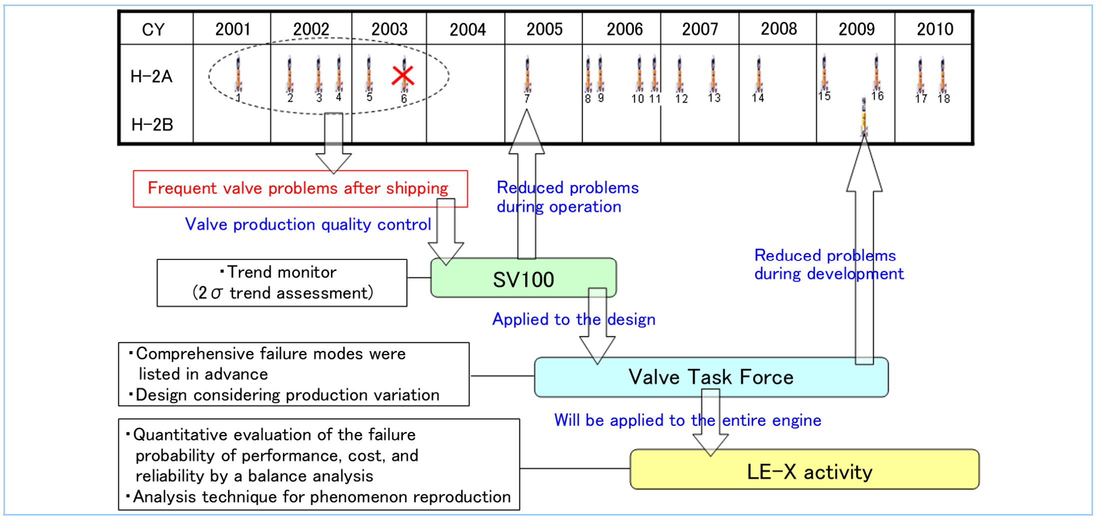

Figure 6 Approach using high-reliability design techniques for a rocket engine

3.1 Production Quality-Improvement (SV100 Tactics)

In the early phase of the H-IIA launch vehicle project, valves often had defects after shipping and assembling. At that time, the design was completed and the vehicles were in mass production. Intensive quality-control during manufacturing was used to reduce the defects at the launch site. To this end, the shipping quality (initial quality) was improved using major characteristic value control (2σ trend assessment). The major characteristic values (leak amount, actuation timing, and others) of each valve were recorded and controlled. When a value exceeded the 2σ deviation, it was considered abnormal, and thus was inspected and technically assessed before shipping. This activity contributed to the successful launchings of H-IIA Flight No. 7 and successors by drastically reducing the defects at the launch site.

3.2 Design Quality-Improvement Activity (Valve Task Force)

A task force initiative was also started to improve valve reliability (under contract with JAXA). Highly reliable design techniques (front-loading design) summarized below were applied to the development of three new valves for the H-IIB launch vehicle.

- Using quality function deployment (QFD), failure mode and effect analysis (FMEA), and event sequence diagram (ESD) techniques, a comprehensive list of concerns about production, operation, and performance was created.
- After thorough study and quantification of all concerns using element analysis and element tests, a design was implemented that reliably satisfied the design criteria while even when variation in production is considered.

This process drastically reduced the problems encountered during development, and led to an on-time, successful launch of H-IIB Flight No. 1. The manufacturing division extended favorable feedback for good productivity.

3.3 Development of the LE-X Engine for a Next-Generation Main First-Stage Engine

In the development of the LE-X engine, the design process developed by the Valve Task Force was refined and applied to the entire engine. The design concept has been completed, and the development of a real-sized combustor has been started (it will be tested in fiscal year 2013). Implementation and element tests for verification are in progress.

3.3.1 High-Reliability Design Techniques

The approach using the quality-control design techniques (described above), refined and applied to the development of the LE-X engine, is illustrated in **Figure 7**. This consisted of three steps, as follows:

(1) Balance of performance, cost, and reliability (Figure 7, left).

Considering performance, cost, and margin against each criteria considering variation in the main controlling factors, such as the engine combustion pressure and turbine inlet temperature, are optimized using optimization theory. The engine specifications are determined based on a good balance of performance, cost, and reliability;

(2) Quantitative reliability evaluation (Figure 7, center).

The failure probability of the main failure mode is calculated with probability design analysis (PDA) considering variation in the load, dimensions, and material characteristics (**Figure 8**), using design analysis techniques such as the finite element method (FEM) and also considering variation in factors described in the FMEA and probability design analysis (PDA). Improving accuracy based on design analysis is important; therefore, appropriate analytical technology, including verification with element tests, is also being developed;

(3) Reliability verification with tests (Figure 7, right).

The design failure probability will be verified and updated using the results of element tests and engine tests to improve the estimating accuracy of the failure probability.

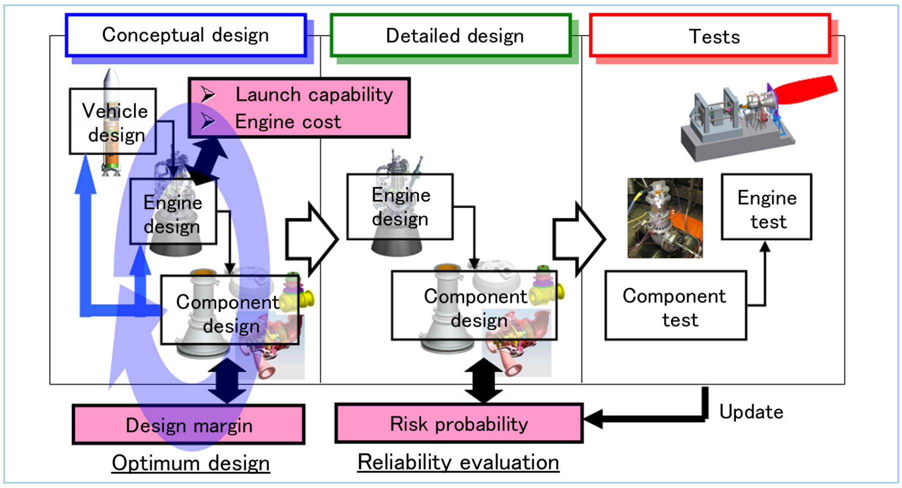

Figure 7 High-reliability design process for LE-X development

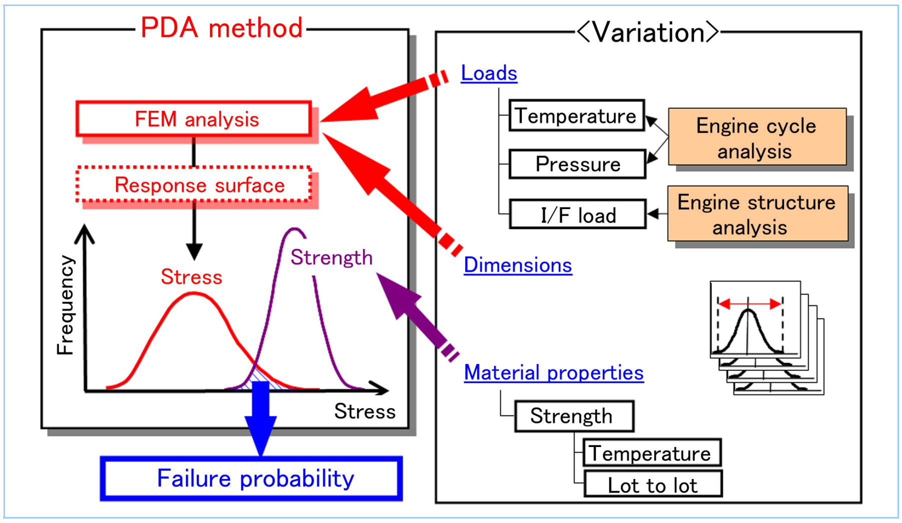

Figure 8 Calculation of failure probability using a design analysis

3.3.2 Development of a Large Combustor

The critical issue when constructing a large-thrust engine based on the EBC is the acquisition of a large amount of turbopump power. For this reason, the key factors considered for the LE-X engine were heat absorption and manufacturing techniques for the combustor to raise the gas temperature to drive the turbine, and performance improvements of the hydrogen turbopump turbine. Research and development of these two factors are in progress. Under the supervision of JAXA, MHI is responsible for the combustor, and IHI Corporation is responsible for the hydrogen turbopump.

Figure 9 shows the development plan for the combustor, including the quality-control design techniques (Section 3.3.1), new manufacturing techniques, reliability improvements, and cost reductions.

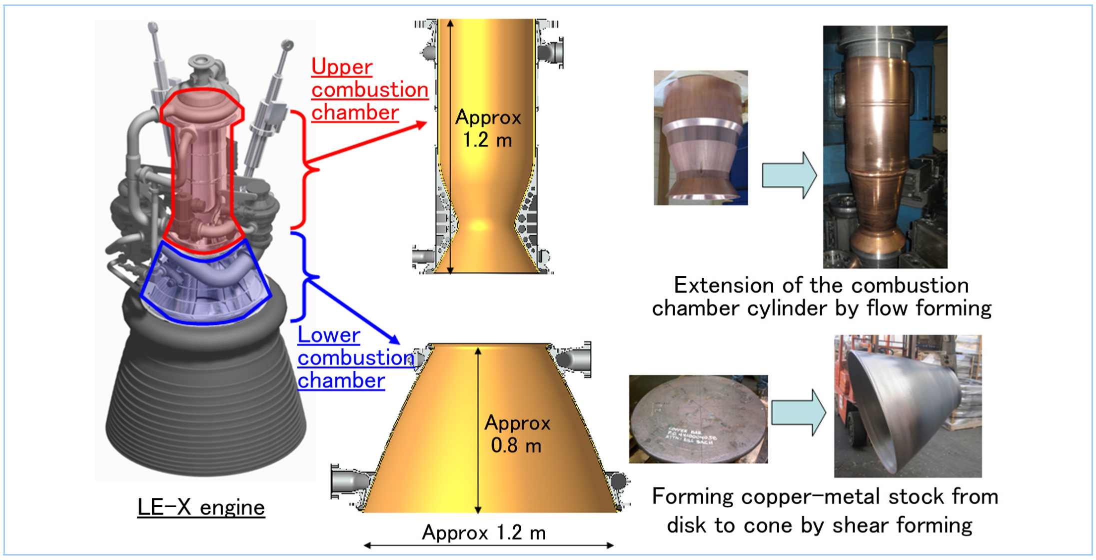

Figure 9 Development of a large combustor

The evaluation of combustion has depended on experiences and tests, or the combustion test results of real engine in the past. On the other hand, LE-X is aiming for short-period development with less trouble by applying the various analytical techniques (**Figure 10**) developed by JAXA and MHI. The combustor design is almost finished, and the procurement of the manufacturing stock and the jig design will be started in the near future.

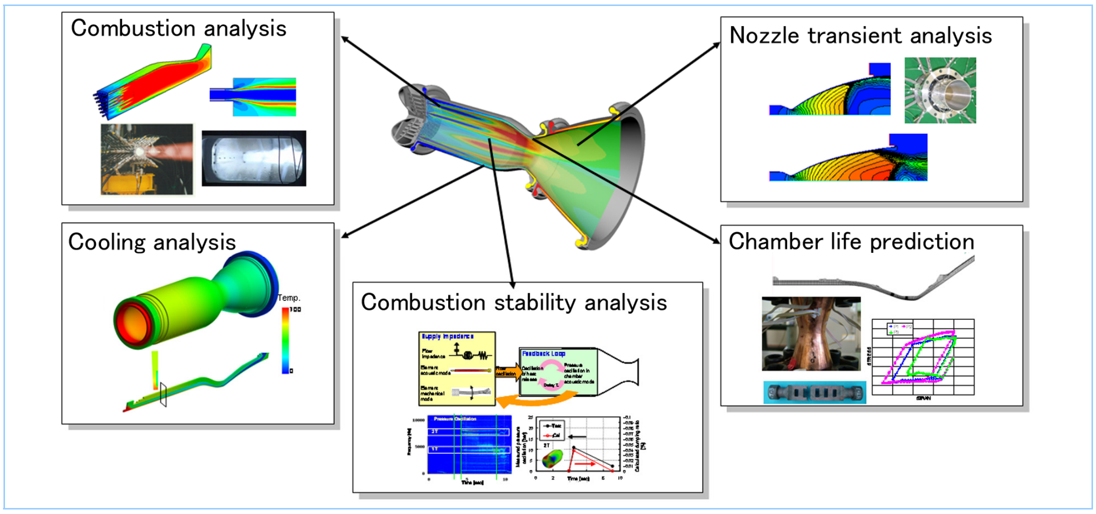

Figure 10 Development of combustion analytical techniques

4. Conclusion

The development of a practical liquid-fuel rocket engine, starting from the introduction of technology from the U.S. and the accumulation of unique domestic techniques through work for purely domestic production, has now attained world-level competence. In the course of this process, we developed world-leading technology to design Japan's original expander bleed engine. The LE-X engine, which integrates these technologies, is now being developed, with the intent of producing the world's best engine.

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