H-IIA Rocket Engine Development

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The first-stage LE-7A and second-stage LE-5B engines of the H-IIA launch vehicle started being developed in 1994, with the LE-5B development completed in 2000, the LE-7A development is still under way to improve the engine further. Failures occurred in the H-II Flight No.5 launch in 1998 where the second-stage engine, the LE-5A, failed and in the H-II Flight No.8 launch in 1999 where the first-stage engine, the LE-7, failed. Development of these engines was continued improving the development plan reflecting the cause of these launch failures. Both engines operated satisfactory in 2001 during the maiden flight of the H-IIA.

1. Introduction

The development of the LE-7A engine, an improved model of the LE-7, was started in 1994 with the main aim of increasing the engine's reliability and reducing manufacturing cost. As of the present time, tests have already been conducted on eight units of the LE-7A engine and development is continuing for further improvement.

In the same year, development of the LE-5B engine, an improved model of the LE-5A, was also started mainly with the aim of increasing the thrust and reducing manufacturing cost. The necessary tests have been made on the five units of the LE-5B engine and the development program has already been completed.

The development of these engines is coordinated by the National Space Development Agency of Japan (NASDA) and carried out under a contract with NASDA by Ishikawajima-Harima Heavy Industries Co., Ltd. for the development of the turbopump, and Mitsubishi Heavy Industries, Ltd. (MHI) for all other engine components, respectively.

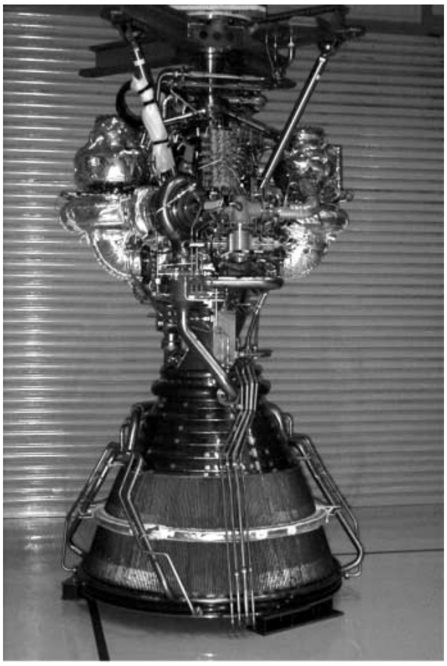


Fig. 1 LE-7A engine

2. Outline of engine

2.1 The LE-7A engine

Fig. 1 shows a picture of the LE-7A engine. This engine has been developed by improving the LE-7 engine which was used as the first stage engine on the H-II launch vehicle. The LE-7A engine operates on the same combustion cycle (staged combustion cycle) as that of the LE-7 but has higher reliability, lower cost and higher performance(1)(2). In order to add the throttling capability for the purpose of enhancing engine performance, the lower nozzle extension is designed as sheet metal construction with film cooling. However, this modification brought about an unexpected problem in the later stage.

2.2 The LE-5B engine

Fig. 2 shows a picture of the LE-5B engine. The LE-5B engine has been developed by increasing the

Fig. 2 LE-5B engine

*1 Nagoya Guidance & Propulsion Systems Works thrust to 14 tons from 12.4 tons of the LE-5A. A change of engine cycle has made it possible to increase the thrust, reduce the manufacturing cost and improve the performance[2][3].

3. Progress and results of the development project

3.1 The LE-7A engine

Table 1 shows the LE-7A engine development schedule. Development of the LE-7A engine was started in 1994 with feasibility tests which were conducted on the LE-7 engine to confirm applicability of the simplification originally planned for the development of the LE-7A engine. The designing work for the manufacture of a prototype engine was started in 1995. Hot firing tests on three units of the prototype engine were started in 1997. Of these three prototype engines, No. 1 and No. 2 engines underwent combustion tests respectively for 23 times/2293 seconds and 23 times/2024 seconds, and satisfied the operating life requirement for the test of 10 times/1900 seconds. This achievement suggests that great progress has been made in the designing work, in particular structural integrity design for the engine, since the development of the LE-7 engine, because the LE-7 engine took almost ten years to reach the same level of operating life requirement. Typical failures that occurred in the prototype engines were:

(1) Melt on the main combustion chamber inner wall surface (preventive measures: change of combustion chamber design and adjustment of film cooling flow rate)
(2) Breakage of preburner mounting bolt (preventive measures: change of flange position and increase of film cooling flow rate)
(3) Breakage of main injector LOX post (preventive measure: increasing radius of broken portion for stress relief)
(4) Buckling of lower nozzle (preventive measures: change of material and addition of stiffener)

After the above-mentioned preventive measures had been implemented, manufacture of the qualification engine designed for actual flight operation was started in 1998, reflecting the test results of the prototype engines. In 1999, qualification tests were started on the two units of the qualification engine. No.1 and No.2 qualification engines underwent combustion tests for 17 times/1501 seconds and 12 times/1618 seconds, respectively, until September 1999, but the following failures were found during these tests:

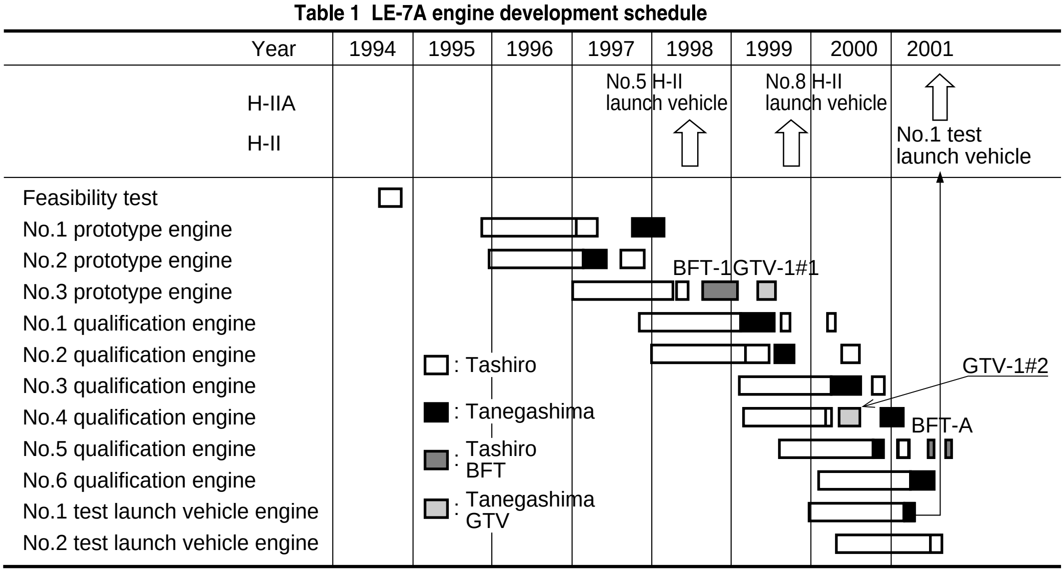
(5) Breakage of preburner fuel element (preventive measure: change of film cooling flow rate to suppress resonance)
(6) Melt on nozzle generative-cooling tube (preventive measures: described later)

In this period, the following failure occurred in No.3 qualification engine during the vehicle system test [Ground test vehicle No. 1 (GTV-1)]:

(7) Large side load in the transient state of engine start and stop (preventive measures: described later).

Failures (6) and (7) resulted from the structure of the lower nozzle extension made of sheet metal with film cooling. It was considered that this problem could not be completely solved within the given period of time, because the H-IIA launch vehicle was scheduled to be launched for its maiden flight at the beginning of 2000. It was therefore decided to use an engine without carrying a lower nozzle extension for the forthcoming flight operation, even though this might lower the performance of the engine, to qualify such substitute engine in time for the launching schedule and to study preventive measures against the said failures at a later stage. The removal of the lower nozzle extension results in a reduction of thrust to 109.5 tons from 112 tons, and of the specific impulse

Table 1 LE-7A engine development schedule



to 430 seconds from 438 seconds.

In November 1999, No. 8 H-II launch vehicle failed in its mission due to stalling of the first stage engine LE-7 during flight. The problem engine was salvaged from the 3 000-meter deep sea bed to investigate the cause of the trouble. The investigation concluded that the cause was damage to the inducer blades of the hydrogen turbopump due to high cycle fatigue accelerated in the low inlet pressure operating condition during flight. As the LH_2 tank is controlled during flight to maintain a pressure difference between the inside and outside of the tank for reasons of structural constraint, the pressure at the inlet to the hydrogen turbopump decreases with altitude. The required conditions were confirmed by simulating the pressure conditions during ground tests. It was known that the so-called rotating cavitation phenomenon occurred in the hydrogen turbopump inducer in the low inlet pressure operating condition. The conclusion of the failure analysis was that the rotating cavitation behavior varied largely due to variance in the characteristics of inducer; that the amplitude of the blade stress was greater; in addition, that other factors such as flow-induced vibration and flaws on the surface of the blades influenced the phenomenon together, and finally, the inducer blades were damaged by high cycle fatigue.

This failure had a very significant influence on the schedule for the development of the LE-7A engine. The launching operation of the H-IIA launch vehicle for its maiden flight scheduled in February 2000 was postponed until the same month of 2001, and the development tests were suspended while investigations to ascertain the cause of the engine failure were being carried out. After this investigation, qualification tests were resumed in June 2000 on the engines, including newly added No. 3 and No. 4 qualification engines. Reflecting the problems disclosed by launching of No. 8 H-II vehicle, the following items were added to the qualification test program:

(1) Expansion of the engine operating range for qualification
(2) Increase of engine verification tests under inlet pressure condition simulating the flight turbopump operating condition
(3) Addition of independent verification test of both hydrogen turbopump inducer and hydrogen turbopump in order to qualify the hydrogen turbopump inducer

Item (1) is to determine the possible flight operating range of the engine considering variations in the characteristics of each engine component with the intention of confirming that the operating range to be qualified has an excess over the possible flight operating range. Accordingly, the qualification test plan was reviewed and the expanded engine operating range for qualification was applied to the hot firing tests that have been made since that time. Item (2) is to test both hydrogen and oxygen turbopumps in the inlet pressure operating condition in which rotating cavitation can occur, with the intention of confirming that the engine is capable of operating even if such operating conditions may occur during the flight. Item (3) is to test the inducers in extreme operating conditions which are not covered by the blade stress measurement or engine tests.

After resumption of the qualification tests, the vehicle system test (GTV-1) were carried out on the launch pad at the Tanegashima island site in August, and the propulsion system performance was confirmed up to a maximum of 150 seconds. In September, three independent qualification engines satisfied the operating life requirement; respectively, 20 times/1991 seconds, 23 times/2 103 seconds and 12 times/2 029 seconds. However, an independent hydrogen turbopump test carried out in the same period revealed the phenomenon that axial vibration accelerated rapidly when the inlet pressure dropped below a certain value, and it was found that such pressure could be experienced by the engine during flight, depending the combination of the engine components. To avoid the above-mentioned condition for safety of the H-IIA maiden flight, it was decided to adjust the engine thrust to a lower level, reduce the turbopump revolutions, and to set the hydrogen tank pressure as high as allowable by changing the vehicle's tank pressurization control parameter in order to ease the turbopump operating conditions. It was also decided to improve the inducer design with regard to suction performance before the second flight. At the same time, a decision was made to use No. 1 and No. 2 H-IIA launch vehicles as the test vehicles without launching any application satellite.

In October of the same year, it was decided to proceed to the acceptance hot firing test of the engine for the No. 1 test launch vehicle. The test was executed in the middle of October. After the three hot firing tests were completed, the following failures were found:

(1) Damage to the LOX tank pressurization duct bellows caused by flow-induced vibration (preventive measure: change the bellows design)
(2) Peeling of nickel plating from the oxygen turbopump casing (preventive measure: not to apply repair plating)

These problems were immediately solved before the additional tests were carried out in November. However, another failure was found in December.

(3) Erosion to brazed jointed the nozzle cooling tube (preventive measures: described later)

The base metal of the nozzle cooling tube is apt to erode when too large an amount of binder is used on the brazing. This failure was prevented by reducing the amount of binder used on the brazing and also by controlling the pressure and temperature of the furnace to accelerate volatilization of the binder. The results of analysis and experiments proved that the nozzle was usable for launching of No. 1 test vehicle. However, in compliance with the judgment made by NASDA on a series of failures found so far, it was decided to further postpone the launching of No. 1 test vehicle until August 2001 and to thoroughly review the development details of the H-IIA launch vehicle (quality revaluation activity) during this six-month period. It was decided that the engine originally planned to be used for the No. 1 test vehicle should be applied to the development of the inducer-improved hydrogen turbopump as No. 5 qualification engine, and accordingly the decision was taken to manufacture a new engine for the No. 1 test vehicle.

From January to April 2001, NASDA and MHI jointly carried out the quality revaluation activity. Utilizing the information obtained from the activity, MHI's engineering, manufacturing, quality assurance and research departments concentrated their efforts on the completion of a new engine for the No. 1 test vehicle, carried out the acceptance hot firing tests three times and successfully completed the third test in April. The new engine was finely prepared for shipment and delivered to the Tobishima Plant of MHI Nagoya Aerospace Systems Works in May to prepare for installation on the vehicle. After delivery of the engine, it was feared that the purchased ducts and piping of the engine might fail to meet the cleanness requirement because of discrepancies found in the methods of cleaning and inspection used by the original ducts aand piping manufacturer. A special inspection was therefore conducted for cleanness focusing on the valve drive system of the engine, and it was confirmed to be acceptable. After this, the engine had no more problems and it was used to launch the vehicle for the maiden flight.

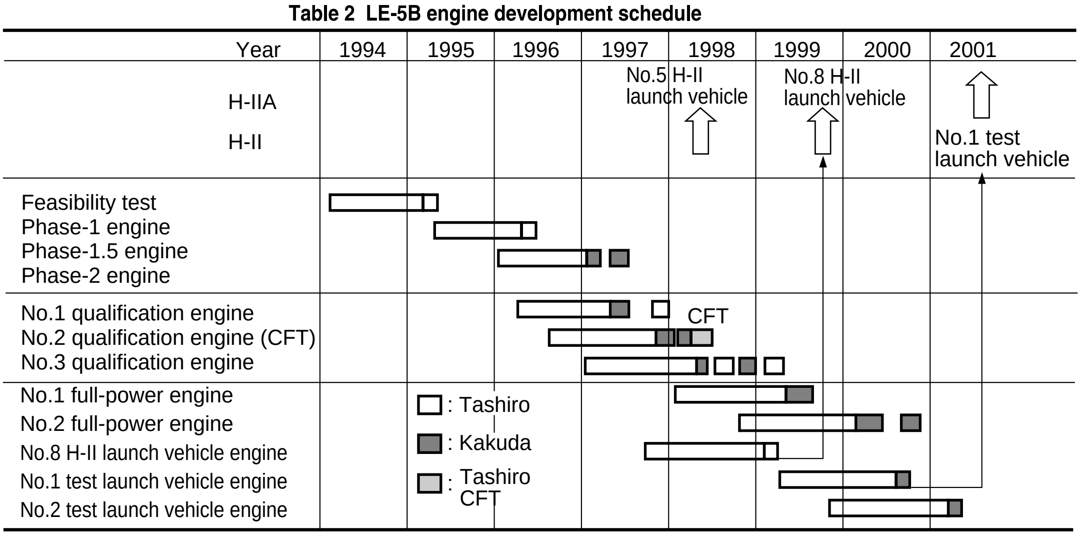
The engine installed on the No. 1 test vehicle operated well, except that measurement of the main combustion chamber pressure was discontinued in the freezing condition that occurred while the vehicle was flying. The thrust and mixture ratios were slightly lower than those shown during the acceptance hot firing test but were still within the range of fluctuation shown by the conventional LE-7 engine of the H-II launch vehicle.

The development of the LE-7A engine is still going ahead as of the present. The qualification test of No. 6 qualification engine equipped with the inducer-improved hydrogen turbopump and the vehicle system test [Battleship Firing Test - Addition (BFT-A)] of No. 5 qualification engine are also being continued with the object of finding and removing new bugs. Design works are being carried out for completion of a fully regenerative-cooled nozzle extension to replace the current nozzle with the sheet-metal lower nozzle extension, like the case of hydrogen turbopump, and also to develop an improved inducer for the oxygen turbopump, of which the suction performance was found to be insufficient in the low inlet pressure operating condition. These new designs will be applied to the construction of a new engine that will undergo a qualification test as No. 7 qualification engine in 2002.

3.2 The LE-5B engine

Table 2 shows the LE-5B engine development schedule. The development of the LE-5B engine was started in 1994. In 1955, an LE-5A engine, which was used for the development test, was modified with its combustion chamber replaced with a copper cooling-channel-milled combustion chamber, and its injector also modified to adjust the injection velocity ratio. The engine thus modified underwent the fea-

Table 2 LE-5B engine development schedule



sibility hot firing test for 8 times/237 seconds for verification of the effectiveness of the expander bleed cycle and the structural integrity of the combustion chamber.

In 1996, the phase-1 engine equipped with the injector designed for the LE-5B engine and the combustion chamber used in the feasibility test underwent the hot firing test for 13 times/931 seconds, including throttling combustion and idle mode operation. The test results of the phase-1 engine were generally acceptable, except that combustion efficiency was low at about 96 percent. The reason of low combustion efficiency was thought that the hydrogen injection temperature of the main injector was lower than the originally designed temperature. Two possible methods of increasing the hydrogen injection temperature were considered: one was to install a swirler on the main injector LOX post to accelerate the propellant mixing, and the other was to extend the combustion chamber to promote heat absorption.

To examine the effectiveness of the first idea, an injector equipped with a swirler was manufactured and subjected to the hot firing test for 3 times/19.9 seconds as a phase-1.5 engine. However, it showed significant combustion instability when the engine was still in the low mixture ratio condition immediately after start of engine. The decision was made to give up the first idea and examine the performance of the latter idea in the forthcoming phase-2 engine qualification test. The injector used on the phase-1.5 engine was replaced with that originally used on the phase-1 engine and subjected to the further hot firing test for 5 times/127 seconds.

The phase-2 engine qualification test was carried out using three engines in total, starting in September 1997 and ending in April 1999. The No. 1 qualification engine, composed of the combustion chamber which was applied to the phase-1 to phase-1.5 engines and the injector slightly modified from that of the phase-1 engine, design of which the fuel element and the face plate cooling flow rate were adjusted to the optimum condition, underwent a series of two qualification tests for 6 times/331 seconds. However, the test had to be discontinued, because the engine was damaged by an external combustion of leaking propellant. No. 2 qualification engine, after being subjected to a series of two qualification tests for 11 times/1361 seconds, underwent another test in combination with the vehicle propulsion system [captive firing test (CFT)] for 7 times/1709 seconds. The test results proved that extension of the combustion chamber led to such a remarkable improvement in the combustion efficiency that No. 2 qualification engine attained the specific impuse of 448 seconds. No. 3 qualification engine underwent a series of four test series for 37 times/8456 seconds in total. In the meantime, the acceptance hot firing tests were conducted on the engines for the No. 8 H-II launch vehicle in February 1999.

Typical failures that occurred in the phase-2 engine were:

(1) Malfunctioning of pneumatic package (preventive measures: tightening of dimensional tolerances of used parts and use of common vent port)
(2) Shifting of engine operating point (preventive measure: installation of flow straightening vane at oxygen turbopump inlet).
(3) Cracking in the hydrogen turbopump disk shaft (preventive measures: application of surface shotpeening and increase of corner radius).

While the phase-2 engine development, there was the No. 5 H-II launch vehicle failure in February 1998 in which the braze joint of the cooling tube of the combustion chamber of the LE-5A engine caused an external leakage, burned the cables of the control system and stopped the engine too early. There was no possibility that this kind of trouble would happen to the LE-5B engine, and accordingly no countermeasures were taken against it, because the LE-5B engine had already employed the copper cooling-channel-milled combustion chamber which had no braze joint. However, since the nozzle has a similar braze joint of the cooling tube in the dump cooling section, in order to ensure reliability of braze joint of the nozzle, a new method was established to examine the brazing condition using the image processing method for photographs taken by high-resolution radiography (microfocus radiography). Using this new method, the cooling tube brazing condition could be examined in manufacturing that made the nozzle reliability higher so far.

The original plan was to finish development of the LE-5B engine when the phase-2 engine test was completed. However, because the hot firing testing range of the phase-2 engine was not always enough to check for the excess range over the rating of 14 tons due to the capability limitation of the NASDA High Altitude Test Facility, there was a possibility that the LE-5B engine might experience a restart thrust shift-up in flight operation – a phenomenon in which the combustion pressure at restart rises above the pressure level at the initial start, as previously occurred in the operation of the LE-5A engine. On reflection, it was decided to improve the NASDA High Altitude Test Facility and carry out additional tests using additional engines to confirm the thrust in a higher range. One of the two additional engines was used for high thrust testing (No. 1 full-power engine) and the other as substitute (No. 2 full-power engine).

No. 1 full-power engine was tested from June to

September 1999 for 13 times/2977 seconds. If an engine which has been adjusted to the acceptance range causes a restart thrust shift-up in flight operation due to its own properties, there is a possibility that the thrust of the engine may exceed the thrust range confirmed by the qualification test. Hence, the tests were carried out to check the coverage of such excessive range.

In November 1999, a failure occurred during launch of No. 8 H-II vehicle. The LE-5B engine was installed on No. 8 H-II launch vehicle as the second stage engine. Although the flight data obtained from this launching operation were not satisfactory, fortunately the second stage engine was shown to have fired successfully following completion of the first stage engine burning even in extremely adverse starting conditions (insufficient chill down and low inlet pressure operating condition), and to have continued stable combustion for about 100 seconds.

Reflecting the failure in No. 8 H-II vehicle launching, the original plan to test No. 2 full-power engine several times was changed, so that it could be used to confirm the performance in a wide range of operation points and over a longer duration of test. The engine underwent the tests for 14 times/5470 seconds. The operating life of the hydrogen turbopump disk shaft and the flow straightening vane, which have been improved by reflecting the failures that occurred in the phase-2 engine, were confirmed. The hydrogen turbopump disk shaft was found to be cracked when the engine was overhauled after a series of tests. However, from the results of the failure analysis, it was judged that hydrogen leaking from an overused mechanical seal disturbed the uniform temperature distribution of the disk shaft and caused the cracking. The decision was therefore made not to take any preventive measures against it.

The engine on No. 1 test launch vehicle is operating well and has not shown any restart thrust shift-up in flight operation.

4. Conclusions

For the development of the LE-7A engine, all problems revealed in the development of the LE-7 engine, including durability of high temperature structure, were completely solved to permit manufacture of highly reliable and low-cost engines. At present, efforts are still being continued to refine the hydrogen turbopump inducer and the fully regenerative-cooled nozzle extension according to the schedule for improvement. The LE-5B engine has passed the development tests satisfactorily in severe conditions and has been completed as a robust engine.

References

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