Development Status and Future Prospects of H3 Japanese Flagship Launch Vehicle

TOKIO NARA[*1] TADAOKI ONGA[*2]
MAYUKI NIITSU[*1] TAKASHI TAMURA[*3]
OSAMU KITAYAMA[*3] YORICHIKA MIHARA[*3]

The H3 launch vehicle is currently under development as Japan's next flagship launch vehicle that will replace the H-IIA/H-IIB. The objectives of the H3 launch vehicle are to ensure "competitiveness in the global commercial market" and "assured access to space", as well as to maintain and strengthen the Japanese industrial base by obtaining orders for commercial satellite launches. Mitsubishi Heavy Industries Ltd. (MHI) has organized the vehicle development as the primary contractor and taken charge of the development of the engine system. The development is currently in the final stage of the test and verification phase. System tests and LE-9 engine firing tests are underway toward the launch of the first vehicle in JFY2021. This report provides overviews the current development status of the H3 launch vehicle and outlines the future prospects.

1. Introduction

The development of the H3 launch vehicle, as Japan's next flagship launch vehicle replacing the H-IIA/H-IIB, started in 2014. MHI have organized the vehicle development as the primary contractor and is proceeding with the development of the engine system in cooperation with the Japan Aerospace Exploration Agency (JAXA).

The primary objectives of the H3 launch vehicle are to ensure "assured access to space" and "competitiveness in the global commercial market." It is intended that the aerospace industrial base is maintained and strengthened by ensuring sales for a constant number of vehicles including commercial satellite launches. To this end, in addition to "high reliability," which is the advantage of the H-IIA/H-IIB, the following three points were reflected in the development specifications based on the results of interviews with customers: (1) competitive launch capability and price, (2) operational improvement at launch site and ensuring launch on desired date and (3) a comfortable vehicle with less vibration[(1)].

The development is currently in the final stage of the test and verification phase. System tests and LE-9 engine firing tests are underway toward the launch of the first vehicle in JFY2021. This report overviews the current development status of the H3 launch vehicle and outlines the future prospects.

2. Overview of H3 launch vehicle

(1) Vehicle system

Figure 1 shows the vehicle configuration of the H3 launch vehicle. The H3 launch vehicle has a launch capability of about 2 to 7 tons to a geostationary orbit (with the condition of ΔV to GSO =1500 m/sec). To seamlessly respond to a wide range of required launch capabilities, the number of solid rocket boosters and the number of main engines for the first

*1 Chief Staff Manager, Space Systems Division, Integrated Defense & Space Systems, Mitsubishi Heavy Industries, Ltd.
*2 Deputy Director, Space Systems Division, Integrated Defense & Space Systems, Engineering Department, Mitsubishi Heavy Industries, Ltd.
*3 Chief Staff Manager, Engineering Department, Space Systems Division, Integrated Defense & Space Systems, Mitsubishi Heavy Industries, Ltd. Ltd.

stage can be selected. The vehicle configuration is represented as H3-abc, with a) the number of main engines for the first stage (2/3), b) the number of solid rocket boosters (0/2/4) and c) fairing size (W:Wide, L:Long, S:Short). Fairing size W has a total length of approximately 16.4 m, which is the same level as fairing size L, and the diameter has been expanded from 5.2 m to 5.4 m to accommodate larger payloads. The minimum configuration, which is H3-30S, is intended to be applied mainly to institutional missions and H3-22L/H3-24L/H3-24W are intended to be applied to commercial missions.

For the satellite interface structure, payload adapters with standard clamp-band sizes (937/1194/1666 mm) will be provided. To flexibly respond to the demand for the launch of multiple small satellites, which has been increasing in recent years, a special payload adapter will be provided.

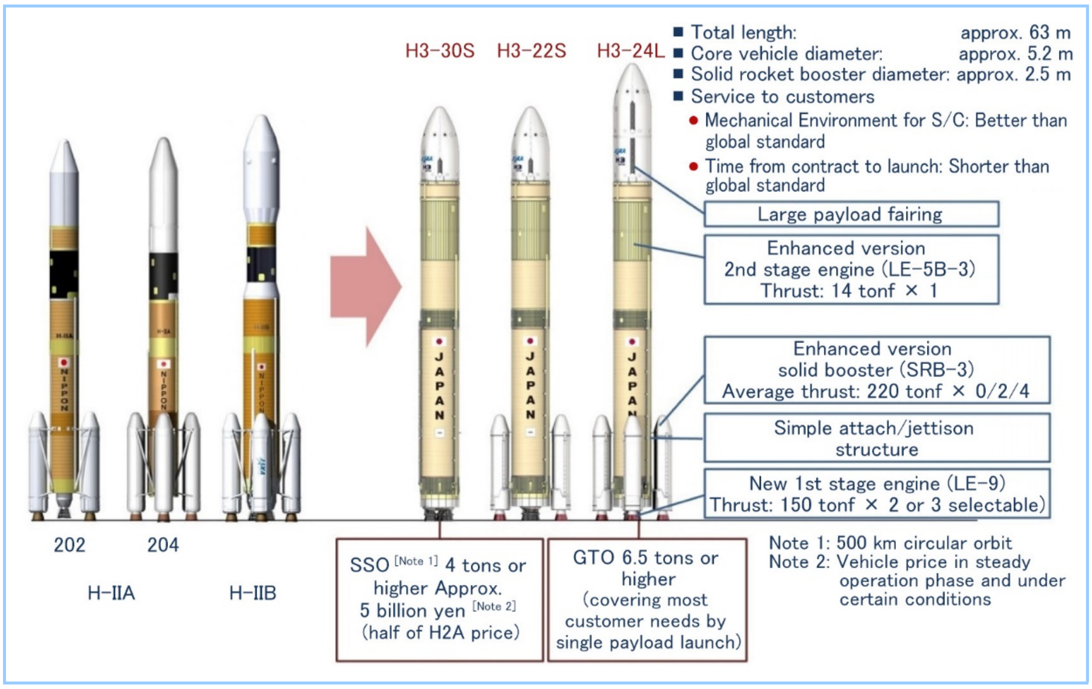

Figure 1 Vehicle configuration of H3 launch vehicle

(2) Vehicle subsystem

For the vehicle subsystem, consideration was given to the balance between following the heritage of the H-IIA/H-IIB technologies and making changes and/or incorporating new technologies to achieve a competitive price. Simplification, commonality and generalization were considered as common policies to both the system and subsystem and automated assembly, processing and inspection were incorporated.

For the liquid rocket engine as one of the major subsystems, the "expander bleed cycle", which is Japanese proprietary technology and has been used successfully in the second stage engines of the H-IIA/H-IIB, was adopted for both the first and the second stages. This engine system offers simple construction, low cost, easy control and high reliability. In terms of the manufacturing of complex components such as injectors, 3D printing technology is used to reduce costs and shorten the manufacturing period.

For the solid rocket booster, the flight-proven technologies and design adopted in the H-IIA/H-IIB/Epsilon are used, securing both reliability and low cost. For the motor case size and materials, nozzle, etc., the flight-proven design is followed, while cost reduction is promoted through the reduction of functions (fixed nozzle), simplification of joint structure, etc.

The structural system and propulsion system of the vehicle are based on the existing design while cost reduction is realized through the simplification of the shape, reduction of special materials and the automation of processes. Examples include the reduction of the number of structural parts comprising propellant tank by using an integrally formed deep spinning dome, the application of an automatic drilling and riveting machine to the assembly of main structures and the use of off-the-shelf commodities (aircraft and automobile parts) for avionics components to the maximum extent possible.

Figure 2 gives examples of cost reduction for the H3 launch vehicle. For detail features of the vehicle subsystem, refer to the previous report[(2)].

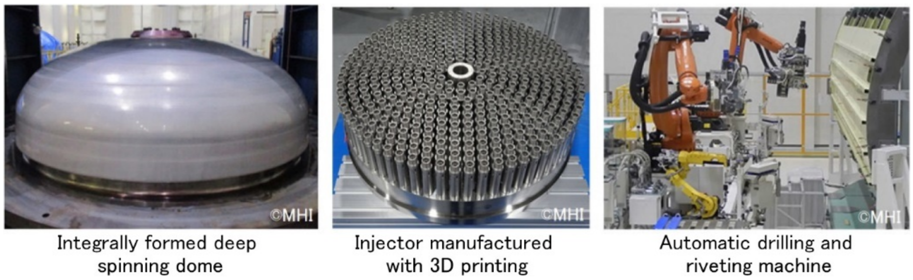

Figure 2 Examples of cost reduction for H3 launch vehicle

3. Progress of H3 development

3.1 Development of LE-9 engine

(1) Progress of development

Figure 3 presents the overall development schedule of the H3. The development is currently in the final stage of the test and verification phase and is progressing with the goal of launching the first flight (TF1) in JFY2021. Although the first flight was initially scheduled in JFY2020, issues were identified during the LE-9 engine qualification test (QT) in May 2020 and the flight was delayed from JFY2020 to JFY2021 in order to address these issues.

In February 2020, the qualification firing tests of an LE-9 engine in the flight configuration commenced. After the 8th firing test conducted on May 26, 2020, openings on the combustion chamber internal wall surface and cracking on the rotor blade of the liquid hydrogen turbine pump (FTP: fuel turbine pump) were found through the inspection. Both of these issues became apparent after the 8th combustion test.

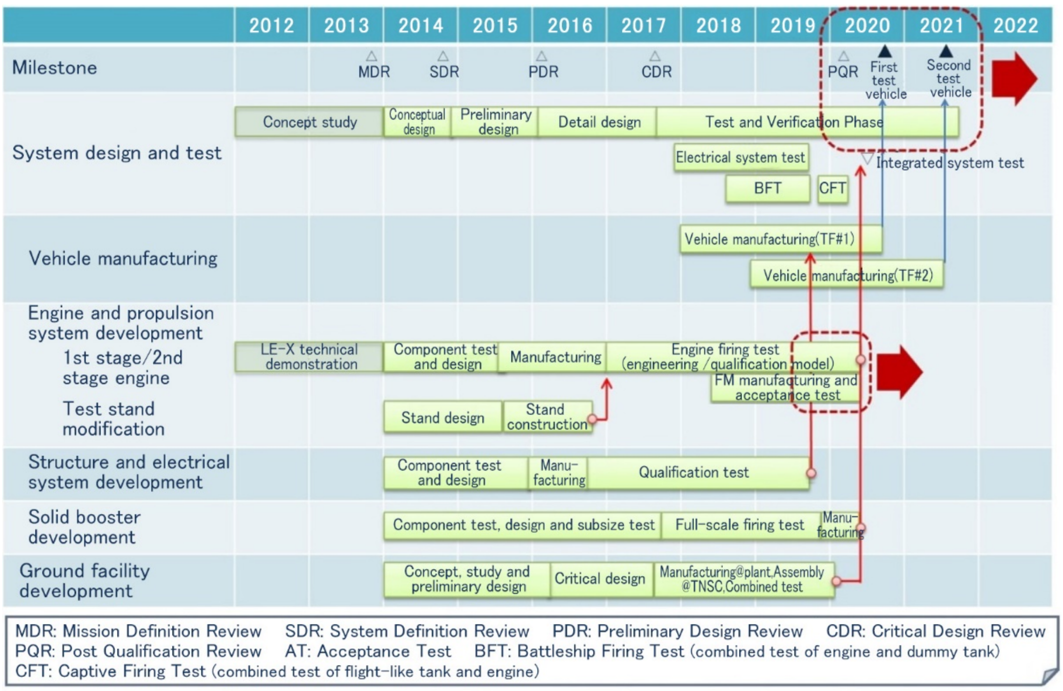

Figure 3 Overall H3 development Schedule

(2) Issues and corrective measure - Openings on combustion chamber

Figure 4 is an overview of openings on the combustion chamber. Fourteen openings with a maximum width of about 0.5 mm and a maximum length of about 10 mm were found along the liquid hydrogen flow path (cooling channel) that cools the combustion chamber. This test was conducted under the operating conditions where the heat load on the combustion chamber was the harshest. As a result of investigating the cause, it was determined that the inner wall became hot and deformed due to the local heat inflow during steady combustion and the surface layer was melted or thinned, which led to the openings

As a corrective measure, the operating conditions of the engine are set so that the temperature of the inner wall surface of the combustion chamber would not exceed the allowable value. In order to define the allowable temperature value, firing tests were conducted with temperature sensors attached to the inner wall surface and the correlation data between the inner wall surface deformation that leads to openings and the wall temperature were acquired and the validity of the analysis prediction of the wall temperature was verified.

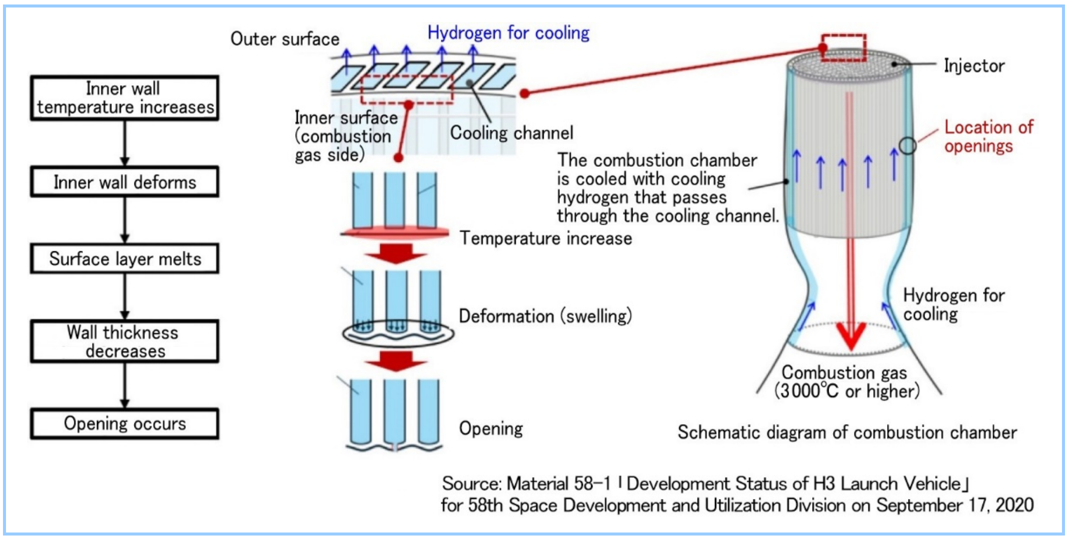

Figure 4 Overview of combustion chamber of LE-9 engine and cause of openings on wall surface

(3) Issues and corrective measure - Cracking on FTP rotor blade

Figure 5 is an overview of cracking on the FTP second-stage rotor blade. Fatigue fracture surfaces were found on two of the seventy-six second-stage rotor blades. In order to investigate the cause, detailed analysis of the actual fracture surface was performed and in particular, the correlation between the fracture origin and the high stress point on the vibration mode and the correlation between beach mark and striation characteristics and load history during QT test were organized to identify the vibration mode involved. The stress generated in that mode was verified by a blade vibration measurement during turbine pump stand-alone test in addition to detailed analysis. In this test, the turbine pump was actually operated and the vibration response (strain) on the turbine blade was directly measured and evaluated. As a result of this cause investigation, it was determined that fatigue accumulated and progressed due to resonance of natural vibration mode, which was initially regarded as having a none-critical effect.

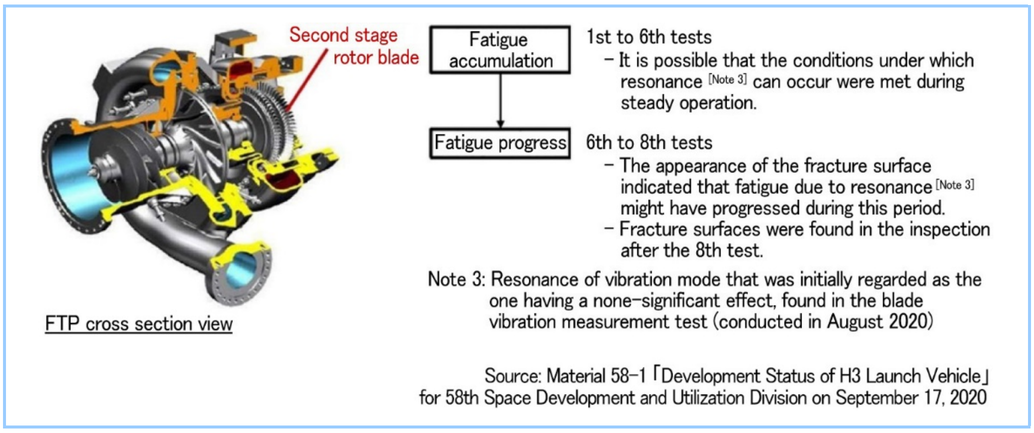

Figure 5 Overview of liquid hydrogen turbine pump (FTP) of LE-9 engine and cause of cracking

As a corrective measure, the turbine blade design (the number of blades and blade shape) was changed to exclude all natural vibration modes from the turbine pump operating range. In addition, although the issue was found in FTP this time, the design of the liquid oxygen turbine pump (OTP) was also changed with the same policy as much as possible.

3.2 Development of system and subsystems

(1) Subsystem test

As shown in Figure 3, the development of the subsystem is almost complete except for the qualification test of the LE-9 engine. The qualification firing test of the LE-9 engine will be conducted after October 2021 using one that reflects the design changes and corrective measures shown in Section 3.1. It is planned that in the first half of the qualification firing test the strain response on the turbine rotor blade will be measured with an FTP/OTP vibration measurement device to verify the validity of the corrective measures.

The status of development and testing of other major subsystems, namely structural, propulsion and electrical subsystems, is summarized as follows. With regard to the structural subsystem, the strength and stiffness tests of each structure have been completed. As for the payload fairing, in addition to the strength and stiffness test, a separation test under an on-ground and atmospheric-pressure environment where the gravitational acceleration is 1G was conducted and it was confirmed that the behavior at the time of separation was as designed (**Figure 6**).

Figure 6 Overview of the H3 launch vehicle structure and fairing separation test

With regard to the propulsion subsystem, a battleship firing test (BFT) of the first stage and a captive firing test (CFT) of the second stage have been conducted to complete verification of the first stage and the second stage including the structural and electrical systems in addition to the propulsion system and engines **(Figure 7**). The BFT of the first stage was conducted in two configurations. i.e. two engine-configuration and three engine-configuration. Eight firing tests in total were conducted with a cumulative time period of about 250 seconds. The CFT of the second stage was conducted using an actual flight hardware. Three firing tests in total were conducted with a cumulative time period of about 1500 seconds. Through these tests, the ignition and shut-off characteristics of the engine, the supply of propellant, the control of tank pressure, the control of engine steering, and the vibration and thermal environment of the vehicle and equipment were verified.

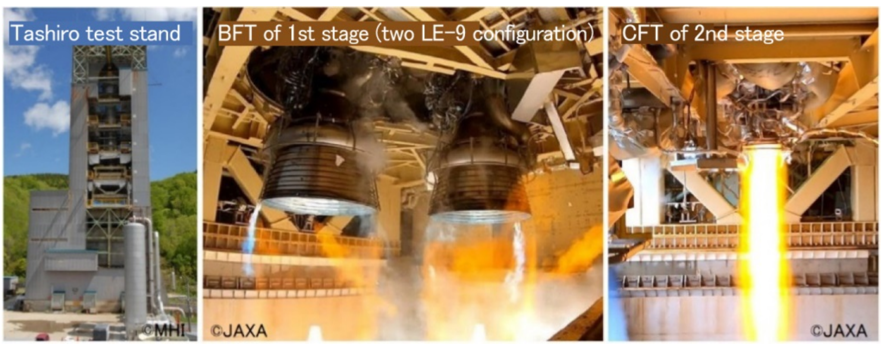

Figure 7 BFT of 1st stage (left) and CFT of 2nd stage (right)

With regard to the electrical subsystem, in addition to the development and testing of the avionics components alone, the electrical subsystem test to verify the functional performance of the entire vehicle with all the avionics components connected through a network has been completed (**Figure 8**). Some avionics components were modified in response to the issues found in the latter phase of the development and have undergone additional verification.

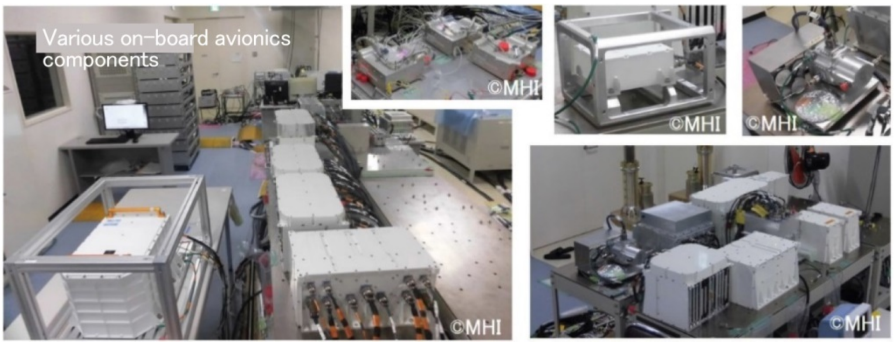

Figure 8 Electrical subsystem test

(2) System test

The first test flight vehicle (TF#1: Test Flight No. 1) i.e. the first- and second-stage vehicles was shipped from MHI Tobishima Plant in January 2021 and the entire vehicle was assembled at the Tanegashima Space Center (**Figure 9**). After that, full-vehicle system tests and verification tests with the vehicle combined with ground facilities have been conducted.

In March 2021, wet dress rehearsal (cryogenic test) was conducted (**Figure 10**). In this test, the vehicle was moved from the assembly building to the launch pad and the all same procedures as the actual launch, from propellant loading, checkout of the functions of each part of the vehicle and the automatic countdown sequence until sending the main engine ignition command, was confirmed. All planned data was successfully obtained and a couple of items were identified which need modification of hardware and operation for flight.

After the wet dress rehearsal, a full-vehicle modal survey, attitude control system test, EMC test and umbilical carrier separation test were conducted as system tests. As for the attitude control system test, the engine steering signal output was measured when the vehicle was excited by a shaker and it was confirmed that the characteristics of the entire attitude control system from input to output were as designed. In addition, as part of the EMC test, it was confirmed that the battery startup and the first stage engine steering operate normally using 270-volt thermal batteries. The first stage engine actuator of the H3 launch vehicle was changed from hydraulic powered to electric powered, so the feasibility of a high-powered control system was one of the important matters to be confirmed.

After this, the full-vehicle system will undergo a CFT of the first stage while standing at the launch pad after the completion of the qualification test of the LE-9 engine. This test is not only the verification of the first stage, but also the pre-flight final verification of the full-vehicle system combined with the ground system.

Figure 9 Full-vehicle assembly of first test vehicle at Tanegashima Space Center

Figure 10 Wet dress rehearsal (cryogenic test)

4. Future prospects

It is planned that two test vehicles (TF1 and TF2) of the H3 will be launched by 2022 and then the H3 will be brought into the commercial market. We have already received a large number of quotations from our customers, which shows high expectation to the H3. On the other hand, in the commercial market, price destruction by SpaceX has progressed and competition has intensified compared to that at the time when the development of the H3 launch vehicle commenced. New launch vehicles developed by other countries such as Ariane 6 of Ariane Space in Europe, New Glenn of Blue Origin in the U.S. and Vulcan of ULA in the U.S. are expected to be brought to market at the same timing as the H3 launch vehicle and further low-price competition is predicted. Demand for launch vehicles is also diversifying, such as the launch of many small satellites for missions of the Constellation program, deep space missions (the Moon and Mars), etc. and is expected to change further due to reduction in launch cost and increase in launch capability.

In order to respond to these changes in the environment and maintain the industry base for the flagship Japanese launch vehicle, the H3 launch vehicle needs to be evolved and enhanced continuously. **Figure 11** presents one example of the future evolution plans. In this plan, the H3 is used to deliver cargo to the Gateway (multi-purpose outpost orbiting the Moon) as an international contribution to the crewed lunar exploration program (Artemis program) planned by the United States. In this plan, the launch capability will be greatly improved by clustering the first stage vehicle.

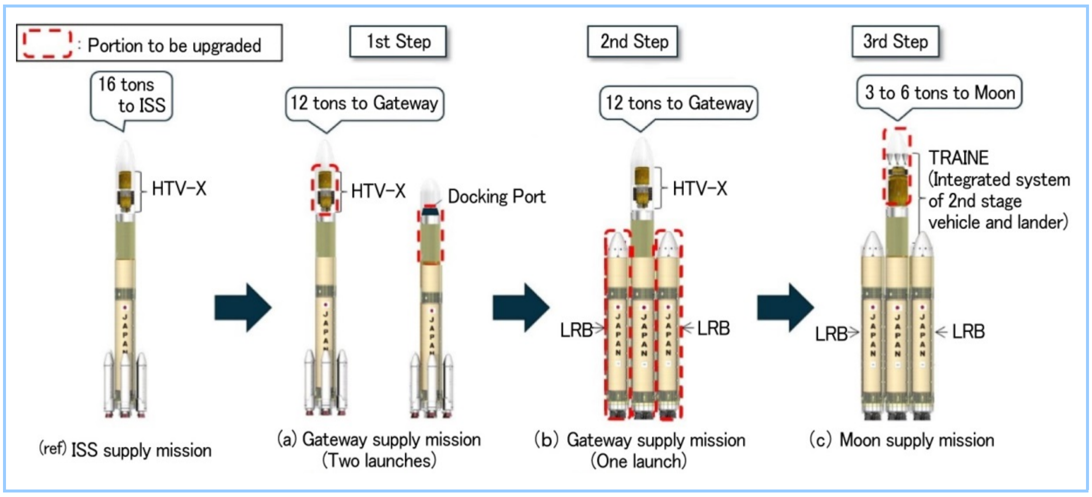

Figure 11 One of the H3 evolution plans

In order to drastically reduce the launch cost, "partial or complete reuse" of the vehicle, which has been put into practical use by SpaceX and has been worked on for launch vehicles developed by various countries, is considered essential. Future plans for flagship launch vehicles and the roadmap for the realization of an innovative future transport system have been examined by a subcommittee established in the Space Development and Utilization Division of the Ministry of Education, Culture, Sports, Science and Technology and an interim report[3] was released in June 2021. In this report, it is planned as the first step that a subscale demonstration vehicle will be launched around 2026 and an actual-operational vehicle will be launched around 2030, in order to realize the reuse of the first-stage vehicle. As the next step, the promotion of complete reuse including the second-stage vehicle is planned, aiming to reduce the launch cost to about 1/10 of that of the H3 by the first half of 2040.

MHI will work on technological development in collaboration with JAXA and related ministries and agencies in order to realize an innovative future transport system in parallel with the short- and medium-term continuous improvement of the H3.

5. Conclusion

The concept design of the H3 launch vehicle commenced in April 2014 and its development is currently in the final stage of the test and verification phase. The development of subsystems has been completed except for the LE-9 engine. The first test vehicle has already been shipped to the Tanegashima Space Center and launch preparations are underway. At the Tanegashima Space Center, the system tests including the wet dress rehearsal using the first test vehicle have been conducted and verification of the full-vehicle system and the combination of the vehicle and the ground facilities has proceeded.

Although the LE-9 engine was found to have issues in the qualification firing test. the design was changed and preparation for another qualification firing test of the engine for which the corrective measure has been taken is underway. It is planned that the first test vehicle will be launched after the completion of the qualification test of the LE-9 and the CFT of the first stage at the launch site. We will cooperate with internal and external parties to conduct the remaining development tests and the launch of test vehicles (first and second vehicle) and complete a reliable vehicle, aiming at bringing the H3 launch vehicle to the commercial market as soon as possible.

With the intensifying price competition and diversifying missions, the commercial market has been changing rapidly compared to that at the beginning of the H3 development. In order to respond to such changes in the market environment, continuous evolution and enhancement of the H3 launch vehicle is essential. In particular, the key to cost reduction is the reuse of the vehicle. We will work on technological development for its realization in collaboration with JAXA and related ministries and agencies.

References

(1) Atsutoshi Tamura, et al., Development of Japan's Next Flagship Launch Vehicle, Mitsubishi Heavy Industries Technical Review, Vol.51, No.4 (2014), p38～43

(2) Tokio Nara, et al., Development Status of H3 Launch Vehicle, Mitsubishi Heavy Industries Technical Review, Vol. 54, No. 4 (2017), p30～37

(3) The Interim Report of the Roadmap Study Group for Realization of an Innovative Future Space Transportation System
https://www.mext.go.jp/b_menu/shingi/chousa/kaihatu/024/toushin/mext_00823.html