Successful Demonstration for Upper Stage Controlled Re-entry Experiment by H-IIB Launch Vehicle

KAZUO TAKASE*1 MASANORI TSUBOI*2

SHIGERU MORI*3 KIYOSHI KOBAYASHI*3

The space debris created by launch vehicles after orbital injections can be hazardous. A piece of debris can collide with artificial satellites or cause a casualty when it falls back to earth, which is an ongoing problem among countries that utilize outer space. This paper reports on a Japanese controlled re-entry disposal method that brings the upper stage of a launch vehicle down in a safe ocean area after the mission has been completed. The method was successfully demonstrated on the H-IIB launch vehicle during Flight No. 2, and provides a means of reducing the amount of space debris and the risk of ground casualty.

1. Introduction

The H-IIB launch vehicle was jointly developed by the Japan Aerospace Exploration Agency (JAXA) and Mitsubishi Heavy Industries, Ltd., to launch the Kounotori ('Stork') H-II Transfer Vehicle (HTV), which carries supply goods to the International Space Station (ISS). The H-IIB launch vehicle has the largest launch capability of the H-IIA launch vehicle family: it can inject a 16.5-ton HTV into a low earth orbit (ISS transfer orbit). **Figure 1** shows an overview of the H-IIB launch vehicle.

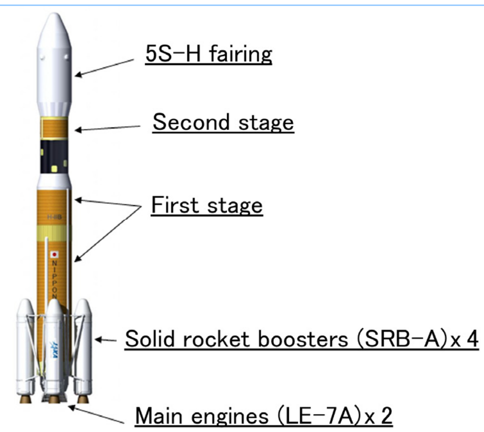


Figure 1 Overview of the H-IIB launch vehicle

The changes introduced in the H-IIB launch vehicle are as follows:

- Enhanced first stage relative to the H-IIA: tank diameter extension, cluster system for two main engines, and four solid rocket boosters (SRB-A)
- Reinforced upper stage (second stage) relative to the H-IIA to launch the HTV
- 5S-H fairing (newly developed to launch the HTV)

H-IIB Test Flight No. 1 was successfully launched from the Tanegashima Space Center on September 11, 2009, and the launch vehicle inserted the HTV to its desired orbit. The second-stage remained in a geocentric orbit after orbiting the HTV. This orbit had the following characteristics:

*1 Space Systems Engineering Department, Space Systems Division, Aerospace Systems
*2 Manager, Space Systems Engineering Department, Space Systems Division, Aerospace Systems
*3 Japan Aerospace Exploration Agency

(1) An inclination of 51.65°, passing over most of the inhabited area on earth.
(2) A low altitude of 200 km, causing it to fall to earth within several days.

Based on this orbit, the second stage is expected to fall randomly in an area between 51° north latitude and 51° south latitude after flying around the earth several times in a geocentric orbit. The second stage is disintegrated by aerodynamic heating and dynamic pressure during re-entry, and most of the fragments will burn out. As a result, the level of risk on the ground is very low. However, considering the planned regular HTV launches, it is desirable to develop a controlled re-entry method to bring the second stage to a safe ocean area to minimize the risk of a casualty as much as possible.[1]

H-IIB Test Flight No. 1 verified that the vehicle has sufficient launch capability as planned. The flight results confirmed that some propellant remained after the HTV separation, so an additional development project was undertaken to achieve controlled re-entry during H-IIB Flight No. 2. Controlled re-entry of the upper stage of a launch vehicle is an advanced technology that has only been attempted on a few actual missions worldwide, such as the Ariane 5 EPS/ATV and DELTA-IV/DMSP-17. This paper describes the development and flight results of the controlled re-entry experiment on H-IIB Flight No. 2.[2]

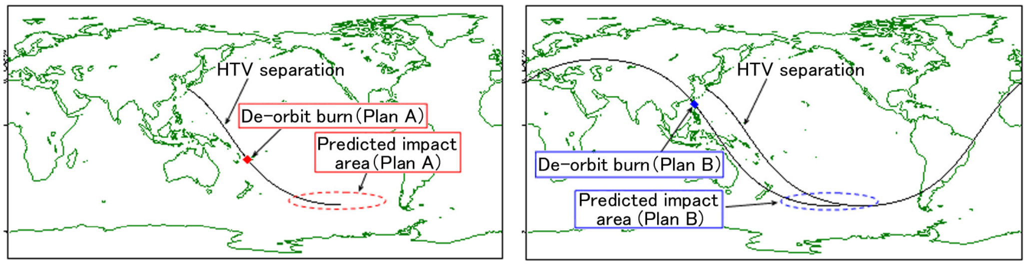
2. De-orbit Scenario and Development Items

2.1 De-orbit Scenario

The development target of the H-IIB controlled re-entry project was the utilization of extra onboard propellant to de-orbit the second stage while maintaining HTV launch capability requirements. The development had to be completed within a year after Test Flight No. 1, and vehicle modifications were restricted to a minimum.

The requirements of the de-orbiting procedure were to ensure that the vehicle would fall down in a safe ocean area, to allow a decision to be made to start de-orbit burn, and to monitor de-orbit burn for safe flight control.

The South Pacific Ocean was selected as the target impact area as it provided the largest safe area over which the second stage orbited after the HTV separation. Two plans were compared to consider trade-offs for the de-orbiting procedure (**Figure 2**).



【Plan A】
Start de-orbit burn immediately after the HTV separation. A deceleration of approximately 300 m/s is required to fall down in the South Pacific Ocean, based on the normal thrust level burn of the second-stage engine for 10 s. A new ground station is required to monitor de-orbit burn.

【Plan B】
Allow the flight once around the earth after the HTV separation, then start de-orbit burn. A deceleration of approximately 50 m/s is required to fall down in the South Pacific Ocean, based on idle-mode burn of the second-stage engine for 60 s. The Tanegashima ground station can monitor de-orbit burn.

Figure 2 De-orbit scenarios

【Plan A】 Start the de-orbit burn immediately after the HTV separation to bring the vehicle down in the South Pacific Ocean.

【Plan B】 Allow the flight once around the earth after the HTV separation and then start the de-orbit burn within visible range of the Tanegashima ground station to bring the vehicle down in the South Pacific Ocean.

Plan A required considerable deceleration from the de-orbit burn to allow the vehicle to fall into the South Pacific Ocean after orbiting the HTV above or near the equator. This plan was not adopted as it would reduce the launch capability of the H-IIB launch vehicle. Development proceeded with Plan B because it could satisfy the launch capability requirements with one-sixth the deceleration required for Plan A by de-orbiting above or near the Tanegashima ground station. Plan B also permitted the use of existing ground stations.

2.2 Development Items

(1) Application of idle mode burn

During de-orbit burn, dispersion of the impact point must be reduced by guidance calculation with an onboard computer. Plan B required minimal deceleration from the de-orbit burn, as well as a low thrust level burn (thrust force: 4 kN) designated ‘idle-mode burn,’ because the normal thrust level burn of the second-stage engine (thrust force: 137 kN) was too large to allow enough time for guidance calculation. Idle-mode burn does not operate the turbo-pump, and is unique to the second stage engine (LE-5B-2). **Figure 3** shows the second-stage engine, and **Figure 4** presents the system diagrams for normal thrust level burn and idle-mode burn.

Figure 3 Second-stage engine (LE-5B-2)

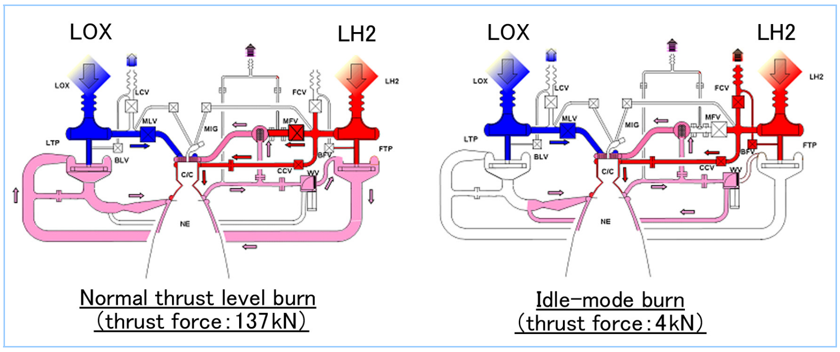


Figure 4 LB-5B-2 engine system diagrams for the normal thrust level burn and idle-mode burn

Idle-mode burn was used for only a short period to re-ignite the H-IIA second stage engine. Therefore, to acquire detailed performance data of idle-mode burn, additional engine qualification tests and flight experiments by the post-mission second stage of H-IIA Flight No.17 were executed.

(2) Development of the ground control system for de-orbit

The ground control system used to activate or deactivate de-orbit maneuver was developed by JAXA. The health status and trajectory of the second stage are evaluated after the flight once around the earth, to ensure safe de-orbit maneuver as planned. The developed system automatically evaluates whether the health status data from each part of the second stage satisfy predetermined criteria, and ensures that the trajectory data before de-orbit burn indicate that the vehicle can be brought down to the targeted impact area. The command allowing de-orbit burn is sent from the ground station after de-orbit is estimated possible. Only when the command is received by the second stage does de-orbit burn begin. **Figure 5** presents an operational image of the ground control system.

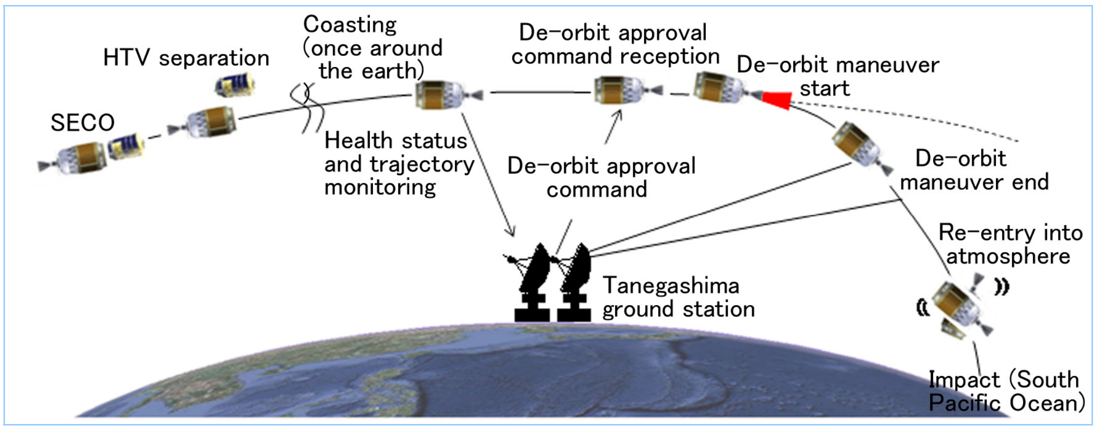


Figure 5 Operational image of the ground control system[1]

3. Vehicle Modifications

The main mission of Test Flight No. 1 was completed in approximately 1,000 seconds, as the HTV was separated approximately 910 seconds after liftoff. In the case of Flight No. 2, the flying time was approximately 6,000 seconds, as de-orbit maneuver was to execute after the flight once around the earth. The following vehicle modifications were required for the prolonged flight time and de-orbit burn:

- Application of thermal protection tape to the onboard equipment to reduce thermal effects during the long ballistic phase.
- Addition of functions to receive the de-orbit approval command from the ground station and begin idle-mode burn.
- Addition of a helium bottle to pressurize the hydrogen tank prior to de-orbit burn.

The amount of hydrazine propellant required for the attitude control system and batteries capacity required to manage the prolonged flight time were evaluated, and additional hydrazine propellant and batteries were estimated unnecessary. H-IIB Flight No. 2 was eventually confirmed to have the required launch capability considering the additional weight of the above modifications and the controlled re-entry was conducted.

4. Flight Plan

Figure 6 shows the trajectory profile of H-IIB Flight No. 2. The H-IIB launch vehicle was to be launched from the Tanegashima Space Center, flying southeast. The vehicle was to separate the HTV within sight of the Guam ground station, 300 km above the Pacific Ocean, approximately 910 seconds after liftoff.

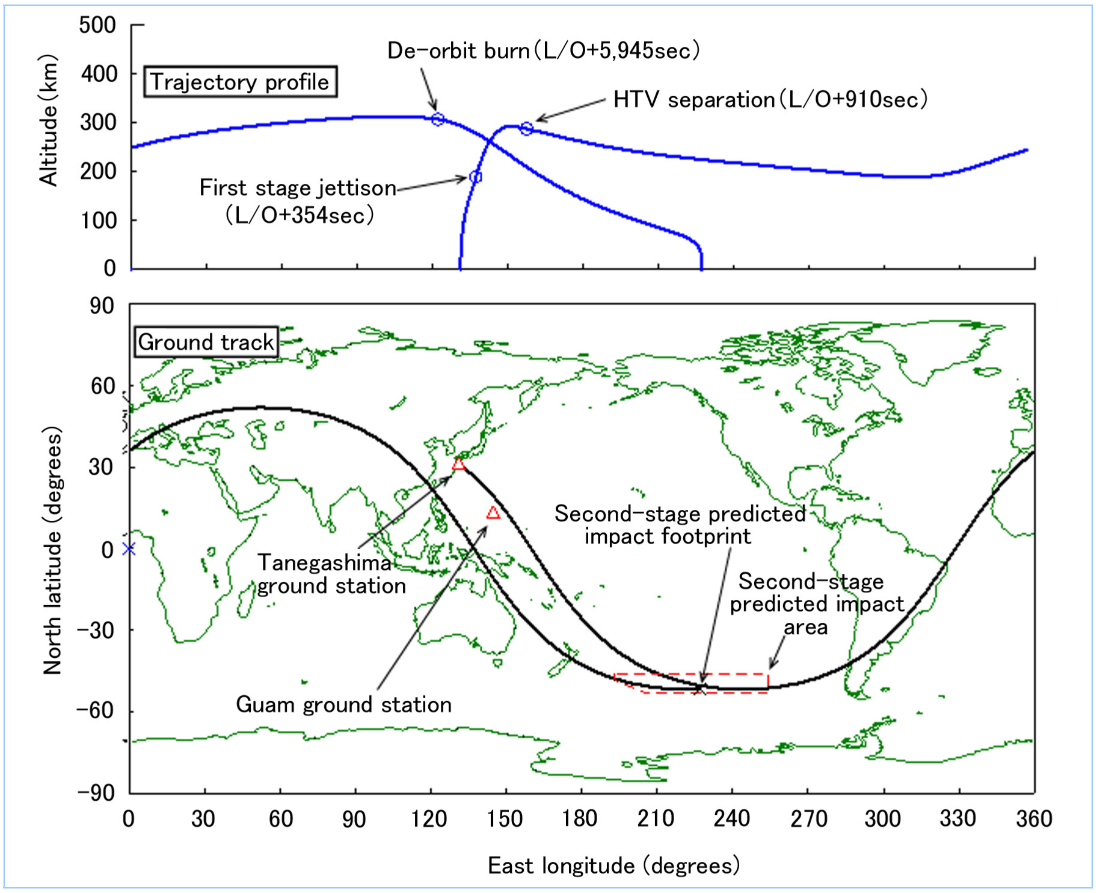


Figure 6 Trajectory profile of H-IIB Flight No. 2

After separating the HTV, the second stage was to change its attitude and move away from the HTV to avoid collision. Once the second stage was sufficiently far from the HTV, it was to adjust its attitude in preparation for de-orbit burn. It was then to begin a ballistic phase making the flight once around the earth; during this ballistic phase, the vehicle was to continue to roll about its axle line (barbecue roll) to maintain appropriate thermal conditions.

Approximately 100 minutes after liftoff, the second stage was to complete the flight once around the earth, and to be visible from the Tanegashima ground station. Idle-mode burn was to start after the de-orbit operation was confirmed by the Tanegashima ground station and the approval command was received. The guidance calculations were to be performed during idle-mode burn to minimize the dispersion of the impact footprint and the burn was to shut off at an appropriate time. The remaining propellants (liquid hydrogen, liquid oxygen, and hydrazine) were to be discharged from the tank, and the ground stations (Tanegashima and Guam) were to continue monitoring the vehicle health status and its trajectory until the vehicle went beyond the horizon. Tumbling rotation (random rotation to place the vehicle's front/rear ends and side faces alternately in the forward position) was to be applied before reentering the atmosphere to cancel any aerodynamic lift.

The first disintegration of the vehicle was assumed to occur at an altitude near 80 km, after re-entry, and almost all of the fragments were to burn out. The remaining small fragments were to fall down in the ocean.

Figure 7 shows the predicted impact area of the second stage, based on the results of fragment impact footprint computation. This area was determined to alert the international shipping and air carrier communities of the potential debris impact hazard.

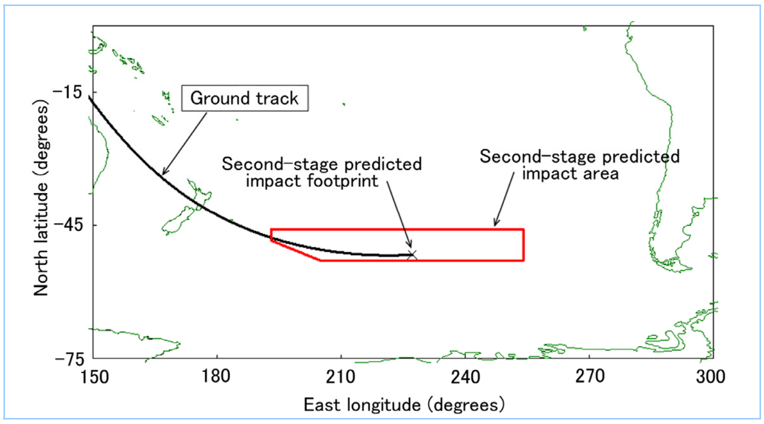


Figure 7 Second-stage predicted impact area

Figure 8 Launching of H-IIB flight No.2
(Courtesy of JAXA)

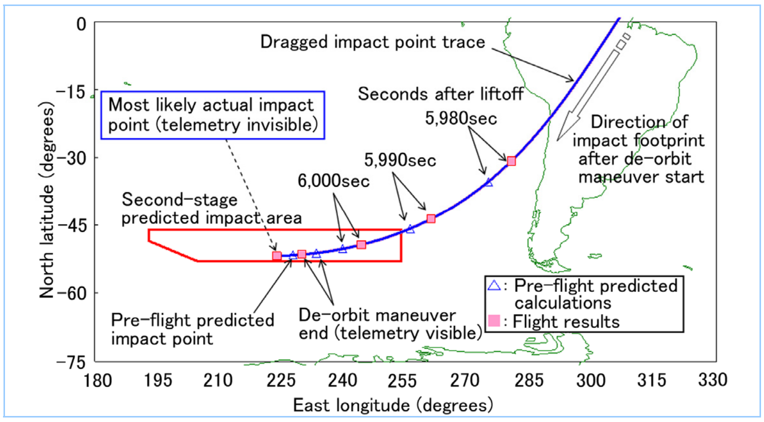


Figure 9 Controlled re-entry result of H-IIB Flight No.2

5. Flight Results

H-IIB Flight No. 2 was launched on January 22, 2011 (**Figure 8**). The flight profile was consistent with the pre-flight calculations, and the HTV was launched into the desired orbit. The second stage was monitored from the Tanegashima ground station after the flight once around the earth, and the de-orbit maneuver was executed as planned. The idle-mode burn performance of the second stage engine was close to the pre-flight calculations, and the main event timeline, such as the burn duration were very close to the analysis predictions. **Figure 9** shows the pre-calculated impact point and the actual impact points based on descent trajectory information after de-orbit maneuver. The impact footprint trace was very consistent with pre-flight calculations, and the health status data acquired from each part of the vehicle were normal. Consequently, all acquired flight data suggested that the controlled re-entry of the second stage was conducted successfully.

6. Conclusions

The development of controlled re-entry with H-IIB Flight No. 2 was undertaken after the completion of Test Flight No. 1. The development was completed in a short period of one year by utilizing H-IIA launch vehicle technologies, as in the case of Test Flight No. 1, and the demonstration flight was successful. One reason for the successful achievement of the project within such a short development period was the good utilization of engineers' skills after the completion of Test Flight No. 1.

The increasing amount of space debris is becoming an international problem, and regulations concerning the upper stage of used launch vehicles which are the source of much space debris, are becoming increasingly stringent. The success of our controlled re-entry demonstrates Japan's leading-edge approach to mitigating space debris.

Controlled re-entry is an innovative technology that can dispose of the launch vehicle safely and quickly from orbit at the end of its mission. The acquisition of this technology illustrates the advanced launching technology in Japan, and also reduces the risk presented by HTV missions launched into low earth orbit, which are expected to continue regularly.

We will continue to improve the technology, for the development of the H-IIA upgrade system, which ignites a third time after a five-hour coasting, as well as the orbit change technique of the next flagship launch system to reduce the amount of space debris.

References

1. Makoto, A. et al., H-IIB Launch Vehicle Result of Test Flight and Plan of 2nd Flight, Aeronautical and Space Sciences Japan, Vol. 59, No. 684 (2011) p. 24-27
2. Kazuo, T. et al., Upper Stage Controlled Re-entry Experiment by H-IIB Launch Vehicle, 28th ISTS Paper, 2011-g-16