Topics

Manned Spacecraft Development Plan from HTV Technical Heritage

By Takane IMADA

Japan Aerospace Exploration Agency, Tsukuba, Japan

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This year will be a major milestone for JAXA with the launching of the new heavy rocket H-IIB and HTV (H-II Transfer Vehicle). Together they will form an important infrastructure for transporting supplies, equipment, and experiment modules to the LEO (Low Earth Orbit) station and will be the basic design of a manned spacecraft in the future. In the previous paper in ISTS in 2008, a preliminary study focusing upon the LES (Launch Escape System) and parametric analyses for its abort system was reported. The missing parts of a manned flight utilizing the combination of HTV and H-IIB are selected as the main structure in this paper. In addition, the progress made in spacecraft design is included along with its development plan in which important development items that have not yet been investigated enough in Japan are identified.

Keywords: Manned Transportation, H-II, HTV, Escape System

Acronyms

- HTV : H-II Transfer Vehicle
- HAB : Habitant Module
- ISS : International Space Station
- IVA : Intravehicular Activity
- JEM : Japanese Experiment Module
- LEO : Low Earth Orbit
- LES : Launch Escape System
- PLC : Pressurized Logistic Carrier
- RM : Re-entry Module
- SM : Service Module
- UPLC : Un-pressurized Logistic Carrier

1. Introduction

The first flight of the HTV (H-II Transfer Vehicle) and H-IIB is planned for September 2009 (Figure 1 shows a photo and an artistic image of the first flight and model). It will be an important milestone in JAXA's long-term vision. HTV development is nearly complete, and the first HTV has already been transported to Tanegashima Space Center for launch preparation.

Fig. 1. First HTV flight model and mission image.

HTV is an ISS (International Space Station) service vehicle and the culmination of what JAXA has been developing for many years in the technical areas of launch vehicles, satellites, and the ISS/JEM (Japanese Experiment Module) program. With the following characteristics, the HTV design is expected to be the basic technology for future projects as an orbital transfer vehicle, a free flyer unit, and a manned transportation system as listed in JAXA Vision 20251).

- Unmanned rendezvous and berthing function
- Large capacity to add extra modules and components
- Multiple redundant avionics and propulsion systems
- Pressurized Logistics Carrier compatible with crew IVAs (Intravehicular Activities)
- Exposed cargo handling capability by robotic arms

A manned spacecraft based on HTV design is one of the candidates. An example was assumed with major dimensions and some other parameters were determined by analysis as shown in the previous paper2). The feasibility analysis has been conducted and this paper reports some of the parts missing in the previous paper.

2. Vehicle Concept

The HTV is an intelligent vehicle and with enough capability to become the base of a manned spacecraft through its technical heritage. (Trade-off studies to estimate the scale of spacecraft are written in the reference document.)

Figure 2 shows the technical relationship between the original HTV and a manned spacecraft. They have a similar target of operation: they transport supplies (or crew) between the ground and LEO. Lunar missions were not selected because of the insufficient launch capability of current
Japanese rockets. The idea of multiple launchers to increase the total launch capability was not selected because of its technical uncertainty for docking and integrating on LEO with affordable resources (weight, time, cost, etc.).

On the other hand, new transporters between LEO and the Earth will be required not only by Japan but also by all international partners after the space shuttle retirement in 2010. Many LEO missions will be planned for such tasks as maintenance of unmanned satellites and space telescopes. A LEO station also has advantages as an outpost to other planets because of the smaller resources needed for construction, lack of gravity, and easy maintenance compared with that of a lunar base.

The selected spacecraft system is as follows:

[Integrated Vehicle]
- Length: 10 m (excluding LES: Launch Escape System)
- Weight: 16.8 metric tons (operational mission, with LES)

[RM (Re-entry Module)]
- Crew: 4
- Diameter: 4 m
- Weight: 5 metric tons

[SM (Service Module)]
- Delta-V: 390 m/s

[HAB (Habitant Module)]
- Volume: 50 m³
- Crew support system includes environmental control

Figure 3 shows the combination of each module in launch configuration. Every estimated value in the preliminary study should include enough of a margin to prepare additional or unexpected requirements in the future. Thus, these values have a certain margin.

3. Subsystems

The HTV is a preferable base design but there are many items that need to be updated or added before building a "manned spacecraft". Particularly, subsystems that have interfaces between multiple modules should be investigated with priority to minimize uncertainties in the module design. As such, the Propulsion System (Reaction Control System: RCS), Thermal Control System (TCS), and Guidance, Navigation & Control (GN&C) System are selected as priority subsystems.

3.1 Propulsion system

The Propulsion System in the SM is similar to that in the HTV but the thrust level of the main engine should be three times greater or even higher (the reason is shown in section 4.3). Technically, the design will not differ significantly from the HTV's.

The thruster system for the RM is shown in Fig. 4. It holds the attitude control and de-orbiting capability, but the translational control capability for the three axes was omitted. RM thrusters should withstand the high heat load during re-entry and all of them shall not face to the direction of re-entry.

The schematic of the RM Propulsion System is shown in Fig. 5. The pressurization system was designed based on the HTV’s, which has two failure tolerances for the contingency acceleration to avoid collision with the ISS. From the propellant tanks, every thruster block has independent isolation valves to prevent failure propagation. This design may be changed or modified in further design phases, but the "two failure tolerances for safe flight" concept will not change.
3.2 Thermal control system

The Thermal Control System (TCS) is a mandatory system for manned spacecraft, and it will be completely different from the HTV’s. The HTV has passive radiation and heaters to control temperatures, but the manned spacecraft should have an active radiation device and a very complex system.

- The RM cannot have a radiation surface because it is covered by a thermal protection system to withstand high heat load during re-entry.
- The RM has air circulation for crew support and it needs heat exchangers to control air temperature.
- The SM should have radiation surfaces for thermal control for both the SM and the RM.
- The RM needs to have components for radiation after separation from the SM (e.g., a Water Evaporator).

Figure 6 shows the total fluid system in the modules. The RM and the SM have fluid interfaces via quick disconnect for heat transfer from the RM to the SM during on-orbit operation. The RM has a pressurized section and heat from the crew support system is removed via heat exchangers. The RM also has water evaporators to remove its heat after separation from the SM.

In this design, the HAB has no fluid interface and can be used as an independent on-orbit module giving it the flexibility for modification or enhancement in the future.

3.3 Guidance, navigation & control system

The HTV has a very complicated avionics system to satisfy the safety requirements as a manned vehicle. This technical heritage can be used for manned spacecraft design as well. Figure 7 shows the schematic for a manned spacecraft, based on the HTV. The differences are as follows:

- A manned spacecraft should have two failure operative functions for crew returning to Earth safely (the HTV is required only to safely depart from the ISS after two failures.)
- The RM has the majority of failure management in the avionics system and should conduct the controlled re-entry flight after any two failures occur. (Ballistic re-entry is not an option after a failure in this plan. An advanced manned vehicle should be designed to relieve the high G-force stress on crew by ballistic re-entry in any case.)

Figure 7 also shows the schematics for both the RM and SM. The RM is designed to conduct the final de-orbit maneuver on its own for the enhancement of convenience as a Japanese vehicle. Both the RM and SM have control systems but the SM uses simplified avionics because it has only to control the final de-orbit maneuver with one failure tolerance after RM separation.
4. Analysis to Determine Parameters

4.1 Launch pad abort

A parametric analysis for abort during the boost phase was conducted in previous studies. The tentative parameters of the LES, such as total weight, dimensions, main motor thrust, and propellant weight were evaluated. In this paper, the launch pad abort analysis result is added for determination of the remaining parameters.

The main motor thrusting pattern is defined in Fig. 8. In the previous analysis, an 800 kN steady-state thrust was used as the tentative requirement, but in this paper, a patterned thrust is used for a more realistic analysis.

The pitch motor firing pattern was determined by referring to the similar system in other vehicles.

- Thrust : 1500 N to 3500 N (parametric study)
- Burning Duration : 1 sec
- Start Timing : 0.5 sec after main motor started

The analysis result is shown in Fig. 10 and Table 1. Because the velocity vector of aborting is fixed at the end of main motor burning, the pitch motor should complete its firing before the main motor stops. As shown in Fig. 10, 1500 N is insufficient for bending the velocity vector and the RM splashdown point is about 600 m from the launch pad. 600 m has not been assessed as a safe enough distance from a fireball caused by the rocket exploding because there is no standard for crew safety in the RM. It is probably enough for the RM, which is covered by the Thermal Protection System, but surrounding operations, such as parachute deployment, are not easy to assess and further investigation is required. So, 2,500 N thrust is selected in this paper mainly because of the RM attitude at the peak point. The attitude (-172 deg) suggests that the LES/RM is flying from the RM side and it is the preferable attitude for their separation. A thrust of 3,500 N causes the LES/RM to rotate too much and the RM is not facing the flight vector at the time of separation.
Table 1. Parametric study result by pitch motor thrust.

<table>
<thead>
<tr>
<th>Thrust of Pitch Motor</th>
<th>Rotation Rate</th>
<th>Max Altitude</th>
<th>Range</th>
<th>Attitude at Peak</th>
</tr>
</thead>
<tbody>
<tr>
<td>1500 N</td>
<td>11.8 deg/s</td>
<td>1,328 m</td>
<td>577 m</td>
<td>-72 deg</td>
</tr>
<tr>
<td>2500 N</td>
<td>19.7 deg/s</td>
<td>1,250 m</td>
<td>897 m</td>
<td>-172 deg</td>
</tr>
<tr>
<td>3500 N</td>
<td>27.5 deg/s</td>
<td>1,143 m</td>
<td>1,146 m</td>
<td>-248 deg</td>
</tr>
</tbody>
</table>

Note: 180 deg is best for RM Separation

Figure 11 shows the G-force during the abort sequence. A 2,500-N pitch motor is selected for this analysis and 14.9 sec is estimated as the time when the LES/RM is at peak point. The splashdown time is 33.9 sec. This means that the LES/RM must prepare separation within 15 sec of main motor ignition, and the parachute should completely deploy within the following 19 sec. This is the most time critical and these values will be the requirements for the separation mechanism and parachute system as the maximum reaction time.

4.2 Rescue plan after boost phase abort

A boost phase abort analysis was conducted as shown in the previous paper, but it lacked the following operation scenario after abort. Figure 12 shows a line of splashdown points (route) after a boost phase abort. To rescue astronauts after the contingency abort, the whole length of the line should be covered.

If we used ships only, six or more are required at predetermined stand-by points to pick up astronauts in the Pacific Ocean after aborting from the launch vehicle. The dotted red circles in Fig. 12 show the 1,000-km radius areas from each stand-by point. If every ship has 22.5 knots as its average speed, the entire area will be covered within 24 hours.

Ordinarily, a combination of helicopters and a carrier ship are used for the sea recovery operation because helicopters have a small operational range. One idea is selected as an alternative way to rescue the astronauts within a shorter time. Figure 13 is a photo and performance table of the ShinMaywa US-2, the latest seaplane developed in Japan. It is available for Search and Rescue operations in the Pacific Ocean around Japan and has a range of more than 4,700 km with superior Short Take-Off and Landing performance. Using the combination of two US-2 seaplanes and one ship, we can cover more than 12,000 km. The blue belt in Fig. 12 shows the coverage by two US-2s; one standing-by at New Caledonia and the other at the Iwakuni Base. They can cover more area than five ships within 10 hours. There is one more advantage of the seaplane. It does not consume fuel during pick-up operations at splashdown points. Helicopters consume fuel while hovering to pick up astronauts, which decreases operational range.

Even though further investigation is required, the use of seaplanes will be the preferable method of rescuing astronauts after a boost phase abort.


4.3 Abort to orbit

"Abort to Orbit" is prepared for the final phase of the launch abort scenario. It allows the crew and re-entry module to escape to orbit by adding a certain delta-V by the propulsion system in the manned spacecraft. The required thrust and delta-V are directly related to the range of rescue determined in section 4.2. The timing to change the abort mode from "Abort to Ocean" to "Abort to Orbit" determines the thrust and delta-V. If we have a longer range for rescue in the ocean, the changing time will be later, in which case a smaller thrust and delta-V are required to put the spacecraft into orbit.

Figure 14 shows the nominal flight path for a manned flight by H-IIB. Figure 15 shows two abort flight paths for aborting at the threshold time of method change. In this case, 0.5 m/s² acceleration and 120 m/s delta-V are required in a manned spacecraft to avoid re-entering the atmosphere. The original HTV has four main engines and 2,000 N to increase delta-V, but the new manned spacecraft needs more than 6,000 N for contingency orbit insertion.

![Fig. 14. Nominal path for H-IIB manned flight.](image)

![Fig. 15. Abort pattern and flight path.](image)

4.4 Nominal recovery plan

Something inherited from HTV analysis data is the de-orbit and re-entry analysis. Based on the HTV operation scenario, "divided de-orbit maneuvers" is selected (HTV conducts three maneuvers for descent). Figure 16 shows a multiple de-orbit burn plan to allow RM recovery from Japan in the neighboring ocean.

Figure 17 shows the splashdown area of the SM and RM. Because the SM generated most of the delta-V for descent, the RM should be loaded with the smaller propellant for de-orbiting.

This design enables the RM to splash down close to Japan (at a predetermined point in Recovery Area-1) and ships can wait at the exact point because the SM has already destructive re-entered over a separate ocean as debris.

If troubles spoil delta-V conduction by the RM, Recovery Area-2 is selectable before RM/SM separation (RM conducts small test maneuvers for a function check prior to the separation). In this case, the RM controls lift and splashes down in an area further from the debris of the SM/HAB and a ship will wait at the expected splash down point.

![Fig. 16. Nominal de-orbit sequence.](image)

![Fig. 17. Nominal recovery area.](image)

4.5 Recovery error

Recovery error was analyzed to estimate the necessary resources to pick up the RM in a nominal case. Table 2 shows the re-entry error analysis results from a previous HTV study and very conservative values were used to translate these errors into the splashing point error. Table 3 shows the summary. A 289-km error is small enough to be corrected by the lift with a conventional capsule, which has a Lift/Drag
ratio around 0.3.

Therefore, most of the splashdown point errors will come from the drift after parachute deployment, which is estimated at less than 10 km from the chasing ship (Ships will chase the capsule based on wind data and current position). The descending RM will probably be seen unassisted from the deck of the ship.

Table 2. Re-entry error sources at 120 km.

<table>
<thead>
<tr>
<th>Interface Error at 120 km</th>
<th>HTV Requirement</th>
<th>HTV Analysis</th>
<th>Result</th>
<th>UFL Value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Value</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inclination Error (deg)</td>
<td>0.03</td>
<td>0.001</td>
<td>-0.001</td>
<td>0.03</td>
</tr>
<tr>
<td>Velocity Error (m/s)</td>
<td>1.00</td>
<td>0.200</td>
<td>-0.600</td>
<td>1.00</td>
</tr>
<tr>
<td>Location (down range) (km)</td>
<td>100.00</td>
<td>38.749</td>
<td>-75.193</td>
<td>80.0</td>
</tr>
<tr>
<td>Location (cross range) (km)</td>
<td>4.00</td>
<td>3.398</td>
<td>0.429</td>
<td>4.00</td>
</tr>
<tr>
<td>Direction Error (deg)</td>
<td>—</td>
<td>—</td>
<td>0.0525</td>
<td></td>
</tr>
</tbody>
</table>

Table 3. Down range errors caused by re-entry errors.

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
<th>Error (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inclination Error (@120km)</td>
<td>0.03 (deg)</td>
<td>±27.9</td>
</tr>
<tr>
<td>Velocity Error (@120km)</td>
<td>1.00 (m/s)</td>
<td>±3.4</td>
</tr>
<tr>
<td>Location Error (@120km)</td>
<td>80.0 (km)</td>
<td>±80.0</td>
</tr>
<tr>
<td>Atmosphere Dispersion</td>
<td>±50 (%)</td>
<td>±119.9</td>
</tr>
<tr>
<td>CL Error (nominal: 0.2)</td>
<td>±25 (%)</td>
<td>±242.6</td>
</tr>
<tr>
<td>CD Error (nominal: 1.11)</td>
<td>±25 (%)</td>
<td>±55.8</td>
</tr>
<tr>
<td>3σ by RSS</td>
<td></td>
<td>±289.0</td>
</tr>
</tbody>
</table>

5. Overall Development Plan

Figure 18 shows the overall development plan for a manned spacecraft. It also integrates the operational flights of the HTV. In the current plan, seven HTV flights are planned as part of the international partnership in the ISS program, and they will be useable as demonstrations of important functions for manned flight by improving the original HTV.

The development plan is divided into the following five sections. All of them are mandatory for a manned transport system.

- Environmental Control and Life Support System
- Manned Spacecraft System/HTV Upgrades
- Manned Re-entry Module Development
- Launch Escape System Development
- Launch Vehicles

If JAXA decides to begin the development, we will have to select the most effective way to advance the development of each item independently and jointly.
5.1 HTV operational flights

The contribution of each HTV operation flight is assessed by the cargo weight that it delivers. If we use part of the HTV as transporter, the weight will not be counted as an international contribution, and an additional flight may be required. In other words, HTV improvements to enhance the cargo transport capability are desirable for not only increasing contributions to the ISS program but also the demonstrations of a manned spacecraft system.

One of the candidates is an unmanned capsule demonstration for re-entry and recovery. This idea will be more reasonable by coupling it with the enhancement of HTV performance.

5.2 HTV improvement

There are several ideas to enhance HTV performance. The following are some examples:

5.2.1 Solar paddle and improved battery system

The original HTV has a very complicated electrical power system. It has four power resources: solar panels, rechargeable batteries, non-rechargeable batteries, and power lines from the ISS.

In the early design phase, the HTV was equipped with non-rechargeable batteries and ISS power interfaces only. However, the additional requirements of an equivalent manned system increased the weight and the design was modified (JAXA did not have experience developing such a redundant system and the estimated HTV weight was too optimistic). Solar paddles were not selected to maintain vehicle size within the interface with the launch vehicle. In addition, non-rechargeable batteries were kept in the HTV to sustain an insufficient solar power system, thus making the HTV power system complex.

A manned spacecraft has several restrictions and will not be allowed to have a large enough body surface to attach solar panels. So, a solar paddle system should be developed to provide enough electrical power to the vehicle. If the HTV incorporates a solar paddle design early on, it will benefit both HTV operations and manned spacecraft development. The HTV will reduce battery weight (8-13 percent of HTV total hardware weight) and increase cargo weight. The solar paddle system will be demonstrated on-orbit before the first manned spacecraft flight. Figure 19 shows the advanced HTV, which has two solar paddles. Solar paddles need some weight for the rotating mechanism and structures but will improve the thermal characteristics and decrease the weight for radiation and heater power.

5.2.2 Structure improvement at rocket interface

The original H-IIB rocket uses the same second stage as H-IIA to minimize its development risk. This stage has a diameter of only 4 m and the interface structure with the HTV is limited to 3.2 m, even though the HTV body has a 4.2-m diameter.

The second stage enhancement plan uses larger tanks and an expanded interface structure, which will be desirable for interfacing with the HTV. The HTV’s weight will decrease or its length will increase to form a compatible structural interface with the rocket. Figure 20 shows one such idea. It has an enhanced length of 2 m and is equipped with a re-entry demonstration capsule and expanded interface ring of 4 m.

5.2.3 H-IIB performance enhancement

The second stage enhancement in the previous section will add certain benefits to the HTV structure design. Yet the greater benefit is the increase in launch capability of the H-IIB. We are conducting an analysis that considers the HTV, a manned spacecraft, and other future missions, such as a lunar inspector or a lunar lander.

It will become our next target after we complete development of the H-IIB rocket by test flight.

5.3 Demonstrations by advanced HTV

As referred to in the previous section, the advanced HTV
will demonstrate some functions of a manned spacecraft. The following demonstrations are being investigated as part of manned spacecraft development.

5.3.1 Re-entry module demonstration

This type of advanced HTV will be possible in the near future. Many scientists who conduct their experiments in the ISS want to get their test results. However, they have only the Soyuz to return samples to Earth after the space shuttle is retired. JAXA and other space organizations recognize the demand and ESA has an expansion plan for the ATV to replace the logistics carrier with a recovery capsule. JAXA has a similar idea. The Unpressurized Logistics Carrier will be modified to carry a capsule and the HTV will keep its cargo transport capability with the PLC in this scenario.

Figure 21 shows an artist's rendering of this type of HTV with all the improvements in section 5.2. It can demonstrate the functions of a manned spacecraft on orbit, and we will be able to experience a recovery operation in the ocean. This is the final configuration as an unmanned spacecraft and will be succeeded by demonstrations with manned spacecraft.

5.3.2 Manned launch flight path

A manned transportation system cannot be developed through spacecraft only. We should achieve crew safety via a combination of spacecraft and launch vehicle. The H-IIB enhancement shown in section 5.2 is desirable not only for cargo transport but also as a demonstration of the manned flight path.

The current H-IIB design does not have a desirable balance in stages as a manned launcher. The H-IIB’s pitch angles during first and second stage boost phases should be carefully adjusted because of insufficient thrust. The estimated gravity loss with the current H-IIB design is almost 15 percent of total launch capability and the H-IIB second stage enhancement will decrease gravity loss and satisfy crew safety with easier pitch angle control.

The manned flight path and rescue in the Pacific Ocean will finally be demonstrated by unmanned flight with a combination of a manned spacecraft and a compatible rocket. The validation flight by enhanced H-IIB and HTV will be very useful because JAXA does not have experience in planning and conducting manned flight paths.

5.4 Demonstrations for manned spacecraft

After or parallel to demonstrations by advanced HTV, flight demonstrations with manned spacecraft will be necessary to verify each safety function systematically. The following is a plan to use the H-IIA and H-IIB rockets as efficiently as possible. Figure 22 shows the launch configurations for these missions.

Figure 23 is an artist's rendering of Demonstration-3, which will be the first manned flight.

[Demonstration-1]
- Unmanned Flight
- H-IIA type202
- Demonstrations for Re-entry Vehicle, Recovery in Sea
  - Total Weight: 6 t + Margin
    i. Re-entry Capsule: 5 t
    ii. De-orbit Module: 1 t

[Demonstration-2]
- Unmanned, but Manned Flight Path
- H-IIA type202 or 204
- Demonstrations for Launch Escape/Abort System
  - Total Weight: 9 t + Margin
    i. Re-entry Capsule: 5 t
    ii. De-orbit Module: 1 t
    iii. Launch Escape System: 3 t

[Demonstration-3]
- Manned Configuration
- Un-manned Flights first, then Manned
- H-IIB
- Demonstrations for On-orbit Flight
  - Total Weight: 14.3 t + Margin
    i. Re-entry Capsule: 5 t
    ii. Propulsion Module: 1.3 t
    iii. Propellant (off-loaded): 1 t
    iv. Launch Escape System: 3 t
    v. Orbital Habitant Module (subset): 4 t

[Demonstration-4]
- Manned Configuration (Enhanced H-IIB)
- Un-manned Flights first, then Manned
- Demonstrations for All Mission
  - Total Weight: 16.8 t + Margin
    i. Re-entry Capsule: 5 t
    ii. Propulsion Module: 1.3 t
    iii. Propellant (full-loaded): 2.5 t
    iv. Launch Escape System: 3 t
    v. Orbital Habitant Module: 5 t
6. Conclusion

One series of preliminary analyses for a manned system showed the feasibility of developing a manned spacecraft from HTV technical heritage. Both the crew support system and the abort system should be developed from the earliest phases of design, but the other systems will be developed based on HTV design. Through the following, we believe that creation of Japanese manned spacecraft via HTV development and a successful flight will be a major milestone.

- The HTV Propulsion/Avionics module will become an upgraded Service Module.
- The HTV Carrier System will be the structural base of the Habitant Module.
- The HTV UPLC will be used for manned flight demonstrations.
- The H-IIB has enough launch capability to put manned spacecraft on orbit.
- The combination of the H-IIB and HTV will be upgraded and JAXA will have experiences in manned operations.

A Japanese manned spacecraft has not received authorization as a JAXA program yet, but we would like to prepare enough to begin immediately upon authorization. In any case, JAXA will complete the first flight of the H-IIB and HTV this September and successfully advance to the next step.

References

1) http://www.jaxa.jp/about/2025/index_e.html