Development of the H-II Transfer Vehicle (HTV)

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After more than ten years of development, the H-II Transfer Vehicle (HTV), a space station cargo transfer spacecraft, successfully docked with the International Space Station on September 18, 2009. The HTV is an inter-orbit cargo transfer spacecraft that carries both pressurized cargo and unpressurized cargo exposed to space. The vehicle is equipped with the crew specifications necessary for astronauts to unload pressurized cargo, and is the first spacecraft other than the space shuttles to transport unpressurized cargo. This paper describes the safety design for crew activities particular to the HTV, newly developed technologies that enable cargo shipment, and the general details of the development, which was carried out under the policy of adopting flight-proven technologies to enhance the reliability and safety of a mission.

1. Introduction

The H-II Transfer Vehicle (HTV), Japan's first space station cargo transfer spacecraft, was launched by the H-IIB launch vehicle, and successfully accomplished its Flight #1 mission to transport supplies to the International Space Station (ISS). The HTV can transport approximately 6 tons of cargo, including both pressurized and unpressurized cargo. It is similar to a satellite in that it is loaded onto a launch vehicle as a payload, as well as in regard to its flight operations. Considering its unprecedented large size, which must be accommodated as a payload, it is structurally similar to a launch vehicle. Since astronauts enter the HTV to unload pressurized cargo after it has docked with the ISS, safety requirements for a crewed configuration are applied. These are not required for conventional launch vehicles or satellites. The HTV is similar to Japan's Kibo laboratory (JEM) in this regard. This paper outlines the development work and describes the technological issues and achievements of the HTV, including the launch vehicles and satellites, as well as the JEM.

2. HTV Configuration

A schematic of the HTV is shown in **Figure 1**. The vehicle consists of four modules: a pressurized logistics carrier (PLC) for transporting pressurized cargo, an unpressurized logistics carrier (ULC) for transporting unpressurized cargo, an avionics module with aviation electronics function, and a propulsion module equipped with a propulsion system for self-actuated flight. The combined configuration of the avionics and propulsion modules is called the main body. It corresponds to the bus module of a satellite, where basic subsystems such as the battery subsystem, navigation and guidance control subsystem, propulsion subsystem, thermal control subsystem, and data handling subsystem are centralized.

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Pressurized cargo loaded in the PLC includes clothing, food, water, and experimental equipment for astronauts. Unpressurized cargo loaded in the ULC include a control momentum gyroscope (CMG), an on-orbit replacement unit (ORU) for the ISS, batteries, and external experimental equipment. **Table 1** compares the HTV with cargo transfer spacecrafts of other countries. A distinctive feature of the HTV is its capacity for transporting unpressurized cargo.

The HTV is able to transport an international standard payload rack (ISPR) internally, since it has a 1.2-m by 1.2-m hatch (entrance). On the other hand, since the European Automated Transfer Vehicle (ATV) uses the Russian docking port, the size of the pressurized cargo is limited by the hatch diameter of 0.8 m. It is true that the ATV has achieved automatic docking with the ISS by using a flight-proven docking port. However, since the HTV puts a greater emphasis on transporting large supplies than on automatic docking, it docks with the ISS using the ISS manipulator. Compared to the space shuttle, the HTV and H-IIB also provide an easier transport environment for pressurized cargo, as shown in **Table 2**.[4, 5]

(1) Cargo capacity for the space station
Supplies: approximately 6 tons
(approximately 4.5 tons)
Pressurized cargo: approximately 4.5 tons
(approximately 3.6 tons)
Unpressurized cargo: approximately 1.5 tons
(approximately 0.9 tons)
(2) Target orbit (space station orbit)
Altitude 350 - 460 km
Angle of orbit inclination: 51.6 degrees
(circular orbit)
(3) Main specifications
Overall length: approximately 10 m
Maximum diameter: approximately 4.4 m
Total weight: approximately 16.5 tons
(4) Mission term
Planned flight time: approximately 100 hours
Emergency standby term: over 1 week
Duration of stay in the ISS
: approximately 30 days maximum
Inside the ( ) shows the value measured by Technical Demonstration Vehicle.

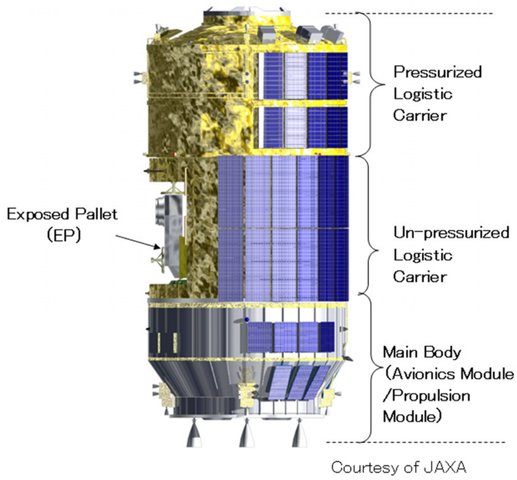


Figure 1 Schematic diagram of the HTV

Table 1 Comparison of resupply spacecrafts of different countries

Resupply spacecraft	HTV (Japan)	ATV (EU)	Progress (Russia)	Space shuttle (US)
Resupply capacity	6 tons	7.5 tons	2 tons	9 tons
Total weight	16.5 tons	20.5 tons	7.2 tons	94 tons
Launch vehicle	H-IIB	Ariane 5	Soyuz	Space shuttle system
Cargo transportation	Inboard and outboard	Inboard	Inboard	Inboard and outboard

Table 2 The environment of the space shuttle and the HTV (pressurized cargo)

	Acceleration in axial direction (G)	Acceleration in helical direction (G)	Acceleration in around x-axis(rad/sec^2)	Angle acceleration in around y, z-axis(rad/sec^2)
HTV/ H-IIB	±5.1	±2.3	±13.5	±11.5
space shuttle	±7.0	±8.0	±70.8	+36.8 −34.8

Figure 2 shows a diagram of the HTV operations.[3]

After the HTV is launched by the H-IIB launch vehicle, it transmits and receives data via the U. S. Tracking and Data Relay Satellite (TDRS), and performs self-actuated flight, sensing its own position with a global positioning system (GPS). Completing a single Earth orbit in around 90 minutes, it adjusts its position to the phase and altitude of the ISS. It directly communicates with the ISS when it is in range, and stops 10 m from the ISS. The HTV is then grappled by the ISS manipulator and docked with the ISS, and the supplies are unloaded. Once the supplies are unloaded, used experimental equipment and other wastes are loaded into the empty vehicle for backhauling. Both the HTV and its used cargoes are burnt out by frictional heat during atmospheric reentry. Up to 6 tons of discarded goods from the ISS can be disposed of in this way.

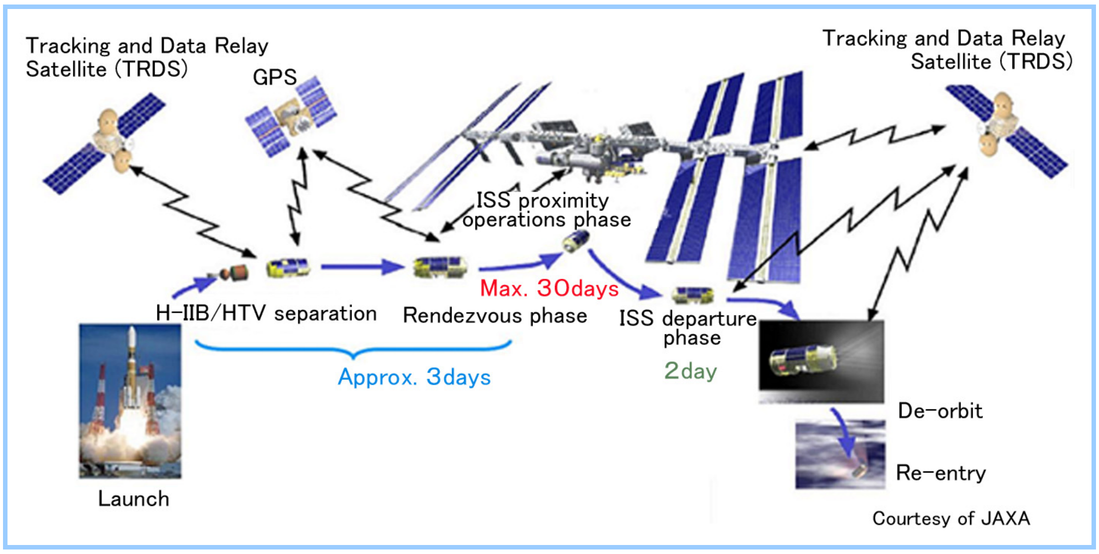


Figure 2 HTV flight operation

3. Development Details and Results

3.1 Development

We initiated the development of the space station cargo transfer spacecraft, which transports supplies to the ISS and disposes of unused supplies from the ISS, to implement Japan's shared obligation in overall ISS operations. The development schedule is shown in **Table 3**. The conceptual design was begun in 1996, and the preliminary design was started in late 1997, after passing through the preparatory design phase. According to the original schedule, the launch of Flight #1 was planned for 2002, but was rescheduled to September of 2009 because of the revised ISS program. In the first stage of the HTV design, we formulated three configurations—short PLC, long PLC, and mixed PLC/ULC, as shown in **Figure 3**—in order to investigate module replacement based on the type of supplies being transported. By recombining the modules to correspond to launch configurations, the HTV offered a number of advantages in terms of transportation efficiency. However, because of its multi-purpose configuration, increased development costs were anticipated.

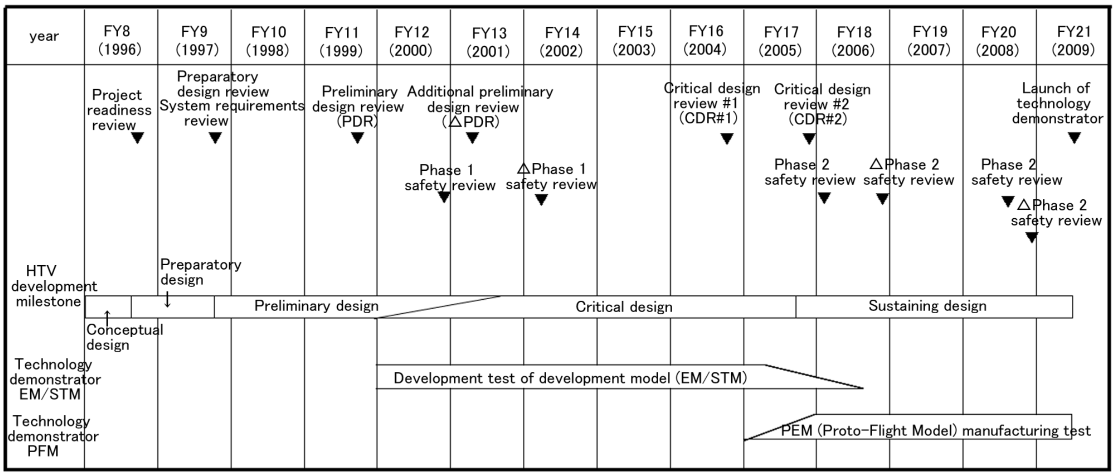
At that time, the space shuttle program was in high gear to build the ISS. In order for Japan to develop a new cargo transfer spacecraft, it was imperative to verify that the resulting spacecraft would be more cost-effective than the space shuttles. To meet this requirement, it was essential to reduce the development costs. Thus, the HTV configuration was focused on mixed PLC/ULC configurations during the preliminary design phase, resulting in the present HTV.

The HTV is a mixture of a launch vehicle, the JEM, and satellite technologies. In the preliminary design phase, Mitsubishi Heavy Industries, Ltd. (MHI), the manufacturer of the JEM and launch vehicles, and satellite manufacturer Mitsubishi Electric Corporation, were working on the development as double-prime contractors, under the supervision of the Japan Aerospace Exploration Agency (JAXA). To distribute the tasks according to respective realms of expertise, it was determined that MHI would take charge of system design, overall assembly, functional tests, and launch site operation work, while Mitsubishi Electric Corporation would handle the flight operations.[6, 7]

Design reviews were conducted during each phase of the design, as well as tests to verify the development, as shown in Table 2. Design reviews at the system level were hosted not only by the manufacturers, but also by JAXA, accompanied by the National Aeronautics and Space Administration (NASA).

It is noteworthy that in addition to the series of design reviews, safety reviews were also conducted. The safety reviews included manufacturer safety reviews, JAXA safety reviews, and NASA safety reviews. The safety reviews were conducted during each phase of the development. We often coordinated with NASA to meet safety requirements and minimize the costs and shorten the timetable. As a result, we were examined by NASA six times, during phase 1 (preliminary design phase), phase 2 (critical design phase), and phase 3 (evaluation phase following system tests).

Table 3 HTV development schedule



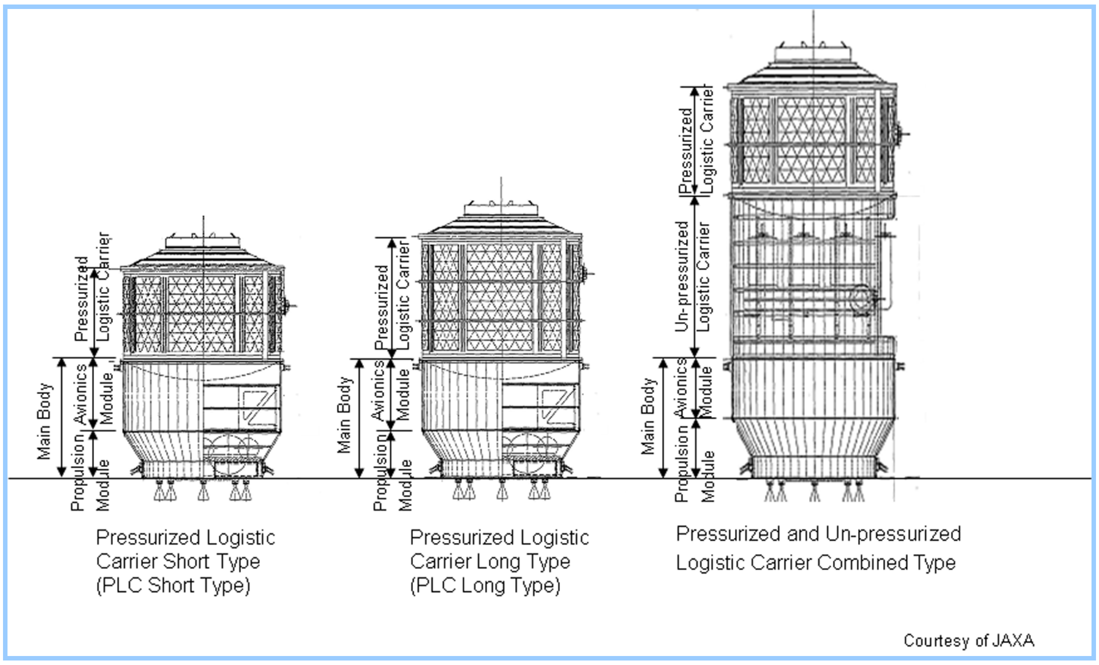


Figure 3 Three HTV configurations considered for the initial investigation

3.2 Results

We emphasized reliability and safety in developing the HTV. We therefore set a policy of carrying out a flight-proven design, using time-tested equipment applied to prior launch vehicles, satellites, and the JEM. Nevertheless, there were issues particular to the HTV that required new development and designs. We describe the safety design issues and the new hardware developed by MHI in the following subsections.

3.2.1 Safety design

Unlike satellites or launch vehicles, we applied a fault-tolerance design to the HTV to ensure a successful mission. The fault-tolerance design includes a One Fail Operative specification (the mission shall be carried out in case of one fault or failure) and a Two Fail Safe specification against a disabling or fatal personnel injury and the loss of the ISS. This is the same design concept that was applied to the JEM, but the safety designs for the following contingencies are particular to the HTV.

(1) Protection against collision

If the HTV collides with the ISS, the damage could cause air leakage from inboard the ISS, and a disabling or fatal personnel injury. Anomalies or failures in the navigation and guidance control subsystems, sensor systems, propulsion subsystems, and battery subsystems, as well as cut-offs in the communication systems, were considered as possible causes of a collision. We therefore designed for the Two Fail Safe specification against collision by multiplexing each function for each cause, or by securing a proper design margin.

(2) Protection against propellant contamination

Both the fuel of the HTV (mono methyl hydrazine) and the oxidant (nitrogen tetra oxide) are harmful to humans. If there is massive propellant leakage from the HTV, and some of the propellant adheres to a spacesuit, harmful substances could be brought into inboard the ISS. Therefore, in the vicinity of the forward thruster, where extravehicular activities occur, valves were triply installed to prevent massive leakage, and control systems were stopped to prevent inadvertent thruster opening during extravehicular activities.

(3) Protection against an explosion in the propellant supply system

If the pressure in the propellant supply system exceeds the maximum designed pressure, in the worst-case scenario, it could cause an explosion, resulting in structural failure of the ISS, as well as a disabling or fatal personnel injury. Excessive pressurization in the propellant supply system because of equipment failure, or abnormal heating caused by a failure in the heating system, were considered as possible causes of pressure increases beyond the maximum designed pressure. To avoid such a situation, we designed Two Fail Safe by placing regulators in serial redundancy and installing shut-off valves in the upper stream.

We also installed a rupture disk designed to prevent excessive pressure on the equipment. This plate is blown out when the pressure exceeds the maximum designed pressure. For protection against heating failures, we designed the switch in the heating control equipment to turn off in order to prevent abnormal heating, once the temperature sensor detects an anomaly.

(4) Protection against battery cell rupture

Rupture of the battery cell because of inappropriate design could cause structural failure of the HTV. As a result, it could cause spacesuit damage, and a disabling or fatal personnel injury engaged in extravehicular activities. A rise in internal pressure, accompanied by increased battery temperature due to a short circuit, inappropriate voltage control, or inadequate pressure-proof container design were considered to be possible causes for such accidents. We controlled such hazards by installing fuses and current-protection circuits, as well as a bursting mechanism that allows the battery to relieve the internal pressure when necessary.

These are the safety designs particular to the HTV. The validity of the design was verified by confirming the drawings, manufacturing quality assurance and testing, and JAXA and NASA reviews.

3.2.2 Structure of the ULC

The primary structural concept of the ULC is a semi-monocoque structure similar to the H-IIA and H-IIB launch vehicles. It provides an unprecedentedly large opening for inserting and removing the exposed pallet with unpressurized cargo, loaded as shown in **Figure 4**. The surrounding areas of the opening are exposed to severe stress concentration during the launch. Accordingly, we placed longerons with ten times the strength and stiffness of members used on general areas to reinforce the opening, and reinforcements to ease the stress concentration. To evaluate the strength of the opening, we conducted elastic–plastic large deflection analysis, using a nonlinear finite element analysis program, and confirmed the validity of the design by comparing the analysis results with the test results.

This technology enabled the HTV to conduct its flight with the large opening, without requiring a panel to reinforce it. **Figure 5** shows the empty exposed pallet, with its supplies unloaded, being inserted into the HTV through the opening. To meet strict weight-reduction requirements, in structures other than the opening, we adopted a design that allows buckling in the semi-monocoque skins in the elastic field during the launch.[1, 2]

3.2.3 ULC mechanical system

To transport the unpressurized cargo, the mechanical system in the ULC fixes the exposed pallet to the spacecraft during the launch, and separates it after docking with the ISS. A long guide rail is attached to the ULC side, and eight wheels are installed on the exposed pallet to roll it into the carrier. (**Figures 6** & **7**)

The wheels are made from a material with self-lubricity (vespel), and coated with a solid lubricant film. The One Failure Tolerance specification (one failure is acceptable) was applied to make the resistance value less than the specified value when removing and inserting the pallet. In order to insert, fix, separate, and remove the exposed pallet, we applied the following three mechanisms that enable the HTV to transport unpressurized cargo.

(1) Tie-down separation mechanism (TSM)

This mechanism ties down the exposed pallet during the launch and separates it when in orbit. It also fixes the inserted exposed pallet when in orbit.

(2) Harness separation mechanism (HSM)

This mechanism holds the connection for the electric separation connector during launch and in orbit, and also separates it when it receives a separation signal.

(3) Hold-down mechanism (HDM)

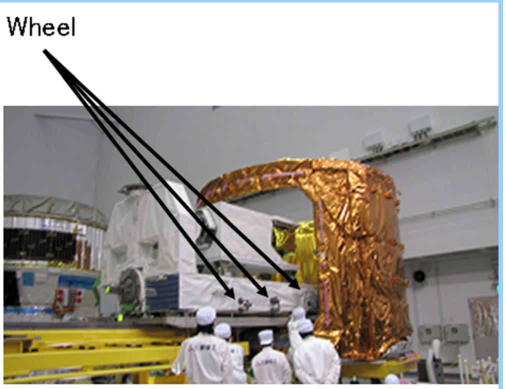
After the exposed pallet held by the ISS manipulator is inserted into the ULC, this mechanism brings the pallet inside and fixes it.


Courtesy of JAXA

Figure 4 HTV with a large opening (exposed pallet installed)

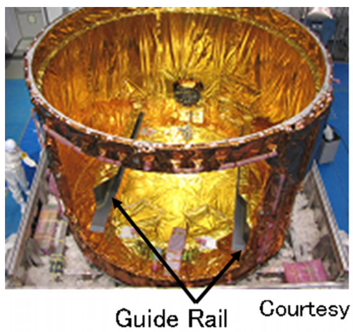

Courtesy of NASA/JAXA

Figure 5 Exposed pallet held by the ISS manipulator



Courtesy of JAXA

Figure.6 Installation of the exposed pallet to the ULC



Courtesy of JAXA

Figure 7 Opening of the ULC and guide rail

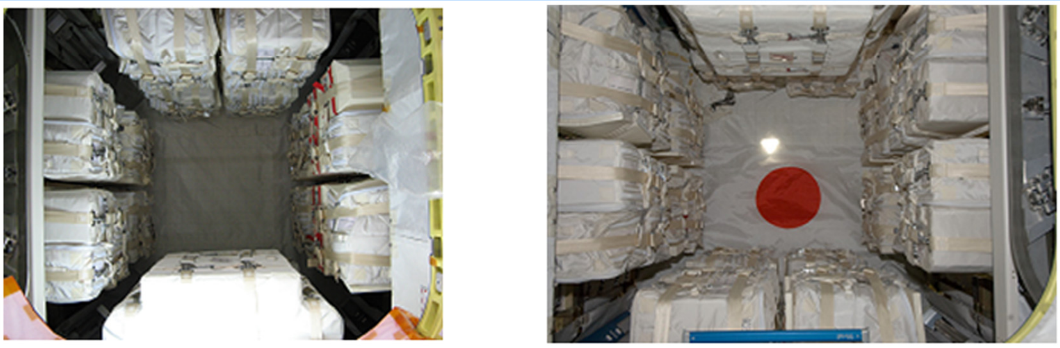
3.2.4 PLC crew specifications

The PLC keeps the inboard pressure at one atmosphere by charging the air, enabling crew members to enter it after docking with the ISS. The supplies (experimental racks, water, and clothing) are loaded in the PLC, as shown **Figure 8**. Crew members enter the inboard section through the joint hatch and carry the supplies out. Used experimental equipment is then loaded in the PLC. As with the JEM, several safety measures are applied to the PLC to protect the crew.

Among the measures described below, the installation of safety valves and thermal controls are the technologies particular to the HTV.

(1) Installation of a debris bumper to protect against debris impingement.
(2) Application of flame proof materials to prevent fire.
(3) Smoke sensor to detect fire.
(4) Installation of an air circulation fan to prevent the buildup of CO_2 exhaled by crew members.
(5) Installation of a safety valve to prevent excessive internal pressure caused by elevated temperature due to solar heating during the flight.
(6) Thermal control to prevent dew condensation resulting from temperature drops while in shade during the flight.

The technologies used on the HTV are similar to those of the JEM. In regard to the air circulation technology, which is essential for human flight, we had to rely on a fan made by overseas manufacturers. We then challenged domestic manufacturers to create a low-noise fan for the HTV, and obtained successful results.



Courtesy NASA/JAXA

Figure 8 Pressurized cargo loaded in the PLC and the Japanese flag set by crew members

4. Conclusion

The launch and flight operations of the first flight of the HTV, a space station cargo transfer spacecraft, ended in success roughly 12 years after the onset of full-scale development, or around 14 years from the initial conceptual design. As a prime contractor, MHI will manufacture the HTV at a rate of one shipment per year from the next operation. Six launches are scheduled. The HTV is equipped with required crew specifications, and various developmental features are anticipated. In light of our initial success, we would like to increase the number of operational spacecrafts and address the future development of other types of HTV, such as return capsules or moon exploration units.

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