On-orbit Demonstration Plan and Development Status of Electrodynamic Tether Technology on H-II Transfer Vehicle

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ABSTRACT

Space debris has been steadily increasing. Cascading effect caused by the collision between the objects would worsen the situation further. To ensure the safety of future space activities, aggressive measures to reduce debris is needed. Since density of debris in the region of 800 km to 1500 km altitude is particularly high, the occurrence of cascade event can be a major obstacle for activities in Low Earth Orbit (LEO). To avoid this situation, JAXA is investigating a service system to capture a defunct satellite or rocket bodies, and remove them from this "crowded" orbit to waste orbit. JAXA is developing Electro Dynamic Tether (EDT) experiment system for on-orbit demonstration as a propulsion system. This paper presents system design, development status, demonstration plan, safety consideration to the ISS and reentry of EDT experiment system.

1 BACK GROUND

JAXA has been investigating to use of EDT propulsion system which does not requires a large amount of fuel. By using the interaction with the Earth magnetic field, EDT can generate a sufficient thrust for orbit transfer over a realistic time period.

JAXA is developing EDT demonstration system as a piggy back payload on H-II Transfer Vehicle (HTV)[1]. HTV is JAXA's unmanned cargo transfer spacecraft to the International Space Station (ISS). JAXA has successfully completed four HTV flights in the period of 2009-2013 and annual three flights are planned in the period of 2015-2017. JAXA plans to demonstrate EDT technology on HTV-6, which will be launched on 2016, as a JAXA's first attempt on-orbit. JAXA has finished critical design phase of EDT demonstration system in September 2014 and undertakes production of flight unit subsequently.

2 HTV AND ITS MISSION OVERVIEW

The HTV is a logistic supply and waste disposal vehicle for the ISS developed by Japan Aerospace Exploration Agency (JAXA). Figure 1 shows the configuration of the HTV. The HTV consists of a Pressurized Logistics Carrier (PLC), an Unpressurized Logistics Carrier (ULC), an Exposed Pallet (EP), an Avionics Module, and a Propulsion Module.

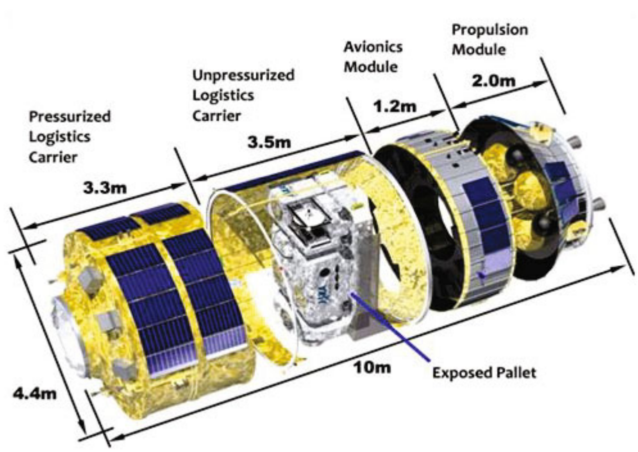

Figure 1. HTV System Configuration

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Cargo and supplies are loaded inside the PLC, and on the EP which is installed in the ULC. The avionics module has the functionality of guidance navigation and control, data handling, communications, electrical power subsystems. The propulsion module has four main engines for orbital maneuvers and 28 Reaction Control System (RCS) thrusters for attitude control. Forward RCS thrusters are placed on the PLC and rear ones on the propulsion module.
JAXA has successfully completed four HTV flights in the period of 2009-2013[2][3] and annual four flights are planned in the period of 2015-2017.

The HTV is designed to be launched by the H-IIB launch vehicle from Tanegashima Space Center (TNSC). The HTV is separated from the H-IIB at about 300km altitude and continues the rendezvous flight to the ISS, whose altitude can range from 350km to 460km, using its own propulsion system based on the onboard flight algorithm and the ground control. When HTV reaches about 10m below the ISS, the ISS crew member operates the Space Station Remote Manipulator System (SSRMS) to physically grab the HTV for capture. The HTV will then be translated and attached to the ISS Node2 module by using Common Berthing Mechanism (CBM). During the attached operation, all the pressurized/unpressurized cargo will be transferred to the ISS either by the crew members or by the ISS Robotics Systems. In turn, disposable cargo will be loaded to the HTV for subsequent de-orbit, re-entry and eventual disposal. Figure 2 shows the HTV mission operation system overview.

The HTV utilizes the Tracking and Data Relay Satellite System (TDRSS) for communication with the HTV Control Center (HTVCC) in Tsukuba. The Global Positioning System (GPS) is utilized for standalone navigation until the HTV establishes the direct communication link with the ISS through the Proximity Communication System (PROX).

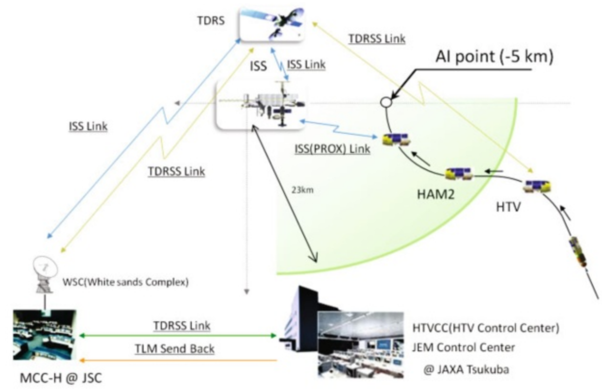

Figure 2. HTV Operation System

3 OVERVIEW OF ACTIVE DE-ORBIT OF HTV

HTV carries out destructive reentry with disposable cargo from the ISS into Earth's atmosphere toward the safe ocean area[4]. HTV Departure operation from the ISS and subsequent re-entry are described as below.
The HTV is released by the ISS robotic arm (SSRMS) at about 10 m under the ISS, and then executes four retrograde maneuvers called IDM1, IDM2, DSM1, and DSM2 during about 70 minutes to ensure a safe departure from the ISS. Subsequently, the HTV is placed in parking orbit, at an altitude 5 km lower than the ISS. After the HTV has finished the process of waiting in parking orbit, it executes three de-orbit maneuvers called DOM (De-Orbit Maneuver) 1, DOM2, and DOM3. Figure 3 shows the HTV flight profile and maneuver sequence during ISS departure and reentry.

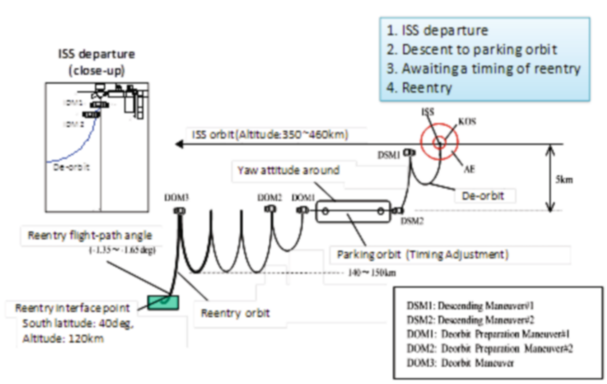

Figure 3. HTV Nominal ISS Departure and Reentry Flight Profile

DOM1 is the first de-orbit preparation maneuver, lowers HTV's perigee altitude and adjust the perigee argument to match the targeted reentry latitude, which is 40 degrees south at an EIF altitude of 120 km. After one revolution from DOM1 in the nominal sequence, the HTV executes DOM2 as the second de-orbit preparation maneuver to lower the perigee altitude. Finally, the HTV enforces DOM3 as the de-orbit maneuver and reenters the atmosphere from orbit.

The reason why the HTV's de-orbit is divided into three maneuvers is to shorten the duration of one maneuver. This is beneficial in terms of visibility from one TDRS satellite and also improves reentry guidance accuracy.

Figure 4 shows the restricted area of ocean into which the HTV should execute safe splashdown. There are two acceptable ocean areas for the HTV's reentry, one of which in the South Indian Ocean and the other in the South Pacific Ocean. The area in the South Pacific Ocean was recently selected for the HTV-1, HTV-2, and HTV-3 reentry due to its wider longitude.

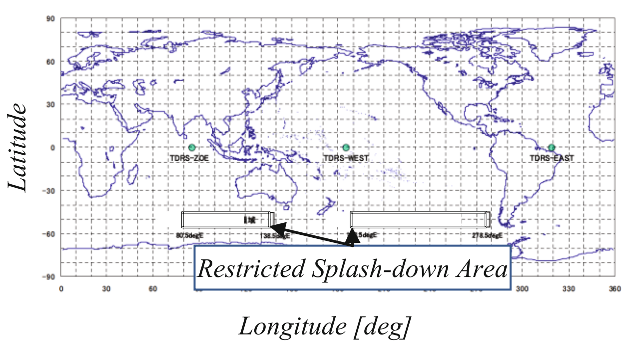

Figure 4. Restricted splashdown area for the HTV

4 ELECTRODYNAMIC TETHER (EDT)

An electrodynamic tether is a promising candidate of deorbit propulsion for future active debris removal systems because of its simplicity, high efficiency, easy attachment to debris, and no need of thrust vectoring. Since the electrodynamic tether utilizes Lorentz force by interaction between current on conductive tether and the geomagnetic field to generate propulsive force as shown in Figure 5, this propulsion system needs no propellant. And also, high electrical power is not required because continuous force by the electromagnetic interaction is enough to generate force to deorbit the debris[5].

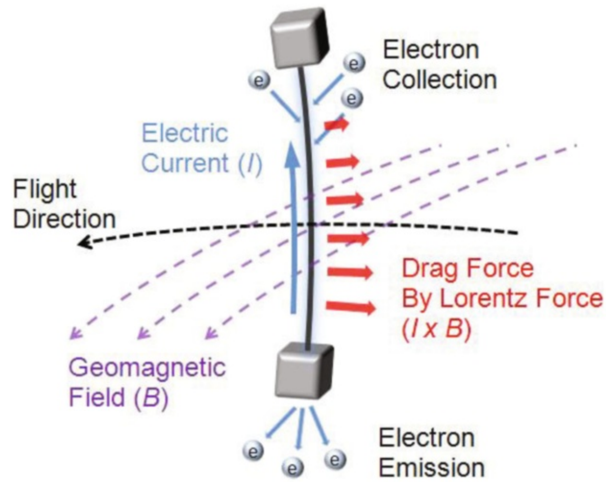

Figure 5. EDT Principle

Electromotive force (EMF) or magnitude of electric potential is shown as Eq .1.

$$V_{emf} = (v \times B) \cdot L \tag{1}$$

where v is velocity, B is the geomagnetic field, and L is the vector from one end of the tether to the other.

Lorentz force is given in Eq. 2.

$$F = (I \times B) \cdot L \tag{2}$$

where I is current flows in the tether.

In configuration of Figure 5, Lorentz force to be worked for the opposite to the flight direction.

5 EDT DEMONSTRATION SYSTEM

JAXA started feasibility study of EDT demonstration on HTV in 2011. Since this demonstration is required to be a low-cost mission and a piggy back payload of HTV, mission design took advantage of the existing functionality of HTV. Feasibility study finalized to use HTV RendezVous Sensor (RVS), which is a kind of LIDAR (Light Detection and Ranging), to observe end-mass motion. By this decision, any active function in end-mass was excluded. It means no wireless communication equipment, GPS receiver, computing and also power system are required on the end-mass. To monitor end-mass and tether motion, a camera system is also installed.

HTV has two RVS on its Zenith surface for rendezvous to the ISS. It realizes laser guided navigation at the final approach from nadir direction of the ISS. RVS provides Range and Line of Sight (LOS) angle measurement to the target reflector on ISS. By using retro-reflector, RVS can search and track the retro-reflector within 730 meter range and it has 40 degrees x 40 degrees field of view. Therefore, only retro-reflector on end-mass is required to observe its relative motion by RVS. In case that relative motion of end mass exceeds RVS field of view, HTV attitude offset can expand RVS field of view. System Image and system block diagram of mission concept are shown in Figure 6 and Figure 7.

End-mass is deployed from HTV zenith side because RVS is mounted on HTV zenith surface. Since the majority of the HTV zenith surface is covered with solar panels, a solar panel is needed to be removed to install end-mass and deployment equipment. By power evaluation with on-orbit data in past three operational flights of HTV, JAXA confirmed HTV solar power system has enough margins and even removing a part of the solar panels, the power balance is satisfied. As a result of power system assessment, JAXA confirmed the best solution is removing a panel on Unpressurized Logistics Carrier to install end-mass and its deployment mechanism. And also it is possible to remove some solar panels on Propulsion Module to install other experimental equipments if necessary. Figure 8 shows HTV-3 nadir view and location of RVS and end-mass deployment mechanism.

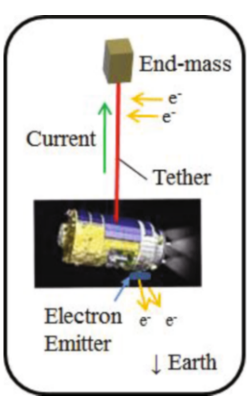

Figure 6. Image of EDT demonstration concept

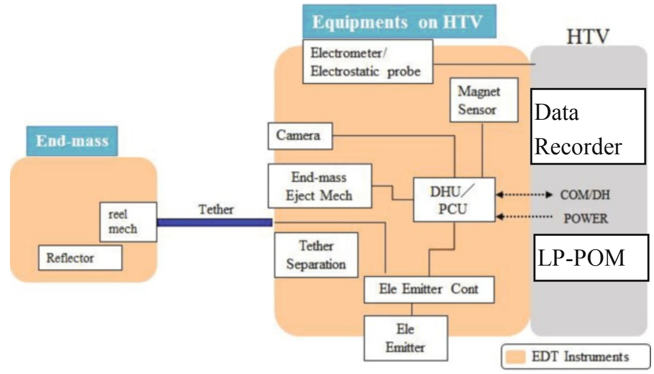

Figure 7. System Block Diagram of EDT demonstration on HTV

Abbreviations in Figure;

COM/DH: Communication and Data Handling Subsystem of HTV
PCU: Power Control Unit
DHU: Data Handling Unit for mission
Ele: Electron

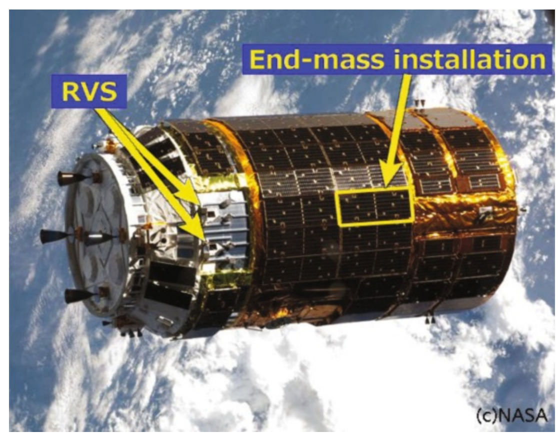

Figure 8. HTV-3 Nadir View and Equipment Location for Updated Concept

Deployment mechanism gives end-mass initial pushing and HTV and end-mass goes away from each other. Given the initial velocity once, end-mass goes apart from HTV dragging the tether, which was wound on a reel. By limitation of RVS tracking capability, tether length must be less than 730 meter. Therefore, JAXA determined to apply tether of 700 meter length.

After ejection of end-mass, demonstration related HTV body charging is conducted. Before activating electron emitter, electric potential of HTV is measured by electric potential meter to assess effect from natural plasma, such as natural electric current on tether and HTV potential behavior. It is expected that induced electromotive force is generated on the extended tether and the potential of the HTV body to be lower for about 100 volts of surrounding plasma potential. By activation of electron emitter, it is expected that the potential of the HTV body, which has been negatively charged, is relaxed to be close to the potential of the surrounding plasma. To realize of potential transient monitoring, LP-POM (Langmuir Probe - POtential Monitor) is installed to measure floating potential of HTV. In order to achieve highly accurate floating potential measurement, a Langmuir probe for measuring the surrounding plasma density is also equipped in the LP-POM. As a pre-demonstration for active and passive potential monitors, JAXA successfully demonstrated Advanced Technology On-orbit Test Instrument for space Environment - mini (ATOTIE-mini) system on-orbit by HTV-4 flight on 2013[6][7][9] and Langmuir probe function will be demonstrated on-orbit HTV5 flight on 2015. Image of HTV with EDT is shown in Fig. 9.

To excite a large current exceeding the natural current on tether, a Field Emission Cathode (FEC) is installed as an electron emitter. At this EDT demonstration mission, carbon nanotube is used as electron emitters [8]. FEC is capable to measure electron emitting current. A magnetometer (MAGS), which was developed for JAXA's SDS-4 (Small Demonstration Satellite-4) satellite mission, is installed to measure geomagnetic field.

On HTV, new data recording function is installed in one of CDP (CCSDS Data Processor). Originally CDP had a telemetry recording function for emergency case. For EDT demonstration, one of two CDPs (redundant one) is modified to implement a new recording function. During operation in critical EDT demonstration, there is also a need for data bandwidth of housekeeping data ensure maximum. However, during non-critical operation, the need for housekeeping date is reduced. By the ability to downlink the experimental data instead of a part of housekeeping data, large amounts of EDT experimental data can be downlinked.

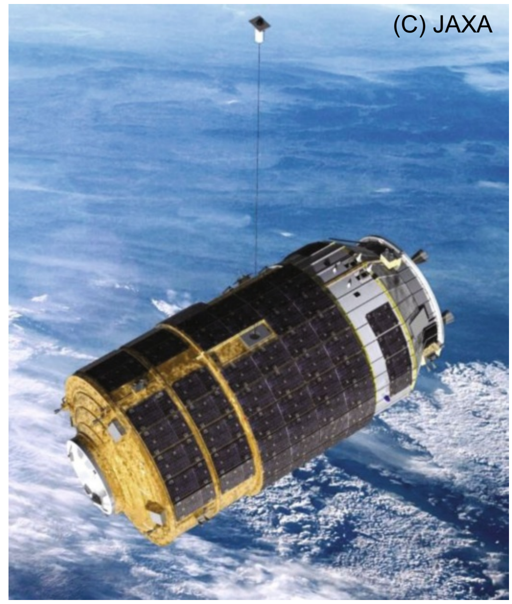

Figure 9 Image of HTV with EDT

6 EDT DEMONSTRATION PLAN OVER VIEW

EDT demonstration includes several steps of experiment and each general demonstration is shown in Table 1.

Table 1 EDT demonstration plan

Step#	Objective	Monitoring by
Step 1	Eject end-mass and deploy tether	Camera & RVS
Step 2	Stabilize tether motion	Camera & RVS
Step 3	Monitor induced electromotive force on tether	LP-POM
Step 4	FEC related demo	
Step 4-1	FEC Electron Emission	LP-POM/FEC
Step 4-2	Tether gathering ion/electron from surrounding plasma	LP-POM/FEC
Step 4-3	Tether motion change by Lorentz force generation	RVS

7 On-orbit Operational Plan/Scenario

After depart from the ISS, HTV goes out from integrated control area of ISS (Approach Ellipsoid, AE). After about 20 km decent from ISS orbit altitude, EDT experiment is initiated. The experiment starts with End-mass deployment from HTV and 7 days of mission is planned. Objective of each demonstration is shown in Table 2.

Table 2 EDT demonstration plan

Day1	End-mass deployment, tether stabilization
Day2	Dynamics observation of tether and measurement of HTV electric potential
Day3	FEC operation and measurement of HTV electric potential
Day4	EDT dynamics monitoring with tether current measurement
Day5	EDT onboard autonomous control
Day6	EDT thrust measurement
Day7	Remove tether and end-mass from HTV

8 DEVELPOMENT STATUS OF EDT DEMONSTRATION SYSTEM

JAXA has almost completed BBM (Bread Board Model) and EM (Engineering Model) development and test for critical design review. On September 2014, JAXA successfully completed a review for EDT demo mission as a critical design review and undertook production of flight unit subsequently. Major milestone for EDT demo mission and HTV flight is shown in Table 3.

Table 3 Major Milestone and Flight Schedule

BBM/EM	Almost completed on Sept. 2014
Flight Unit manufacturing and test	Start on Oct. 2014
Post Development Review	July 2015
HTV-6 Flight	Late 2016 (Calendar Year)

9 SAFEY CONSIDERATIONS

To conduct EDT demonstration, there are two safety restrictions. One of them is safety to the ISS during HTV approaching/attaching/departing operations. The other is safety related reentry of the HTV.

9.1 Consideration For Iss Safety

Safety review for EDT demonstration related the ISS is divided in two part, and those are Phase-2 safety and Phase-3 safety review. Generally Phase-1 review is required at the initiation of mission design phase, but it was agreed by safety review panel to hold Phase-2 review which covers both Phase-1 and Phase-2 review in view of the complexity of the EDT system. Phase-2 safety review for system design review will be held in late 2014 or early 2015 and Phase-3 safety review will be held in late 2015.

To initiate safety review, hazards are needed to be identified and control method to each hazard must be defined. JAXA identified seven unique hazards for EDT Demo Mission. Not unique hazards, those are applied whatever the device in other words, are such as material flammability, material toxic off-gas, shattering material (glass material), EMC, and structural failure. Identified EDT system unique hazards are shown in Table 4.

Table 4 EDT system unique hazards

Hazard#	Hazard Title
1	Removed tether recontacts with the ISS
2	Structure Failure
3	Inadvertent release of end-mass
4	Inadvertent actuating of FEC
5	Sharp edges or a pinch point
6	Touch temperature for EVA crew
7	Electrical shock to EVA crew

Hazard-1 is for recontact of tether and end-mass with the ISS after separation from HTV. Tether and end-mass is needed to be separated from HTV before reentry maneuver to prevent collide with HTV's critical equipment. The 700 meter tether with end-mass is cut off at the HTV in the end of the experiment, and it ascends about 10km at the maximum. Since the HTV nominal orbit to start reentry maneuver is at approximately 5km below the ISS, the end-mass can collide with the ISS if the experiment is planned at this nominal altitude. Control for Hazard1 is to change the altitude of EDT demonstration. The experiment does not start (i.e. the end-mass is not ejected) until the HTV is at 20km below ISS orbit and 20 Nautical miles far from ISS by maneuvers. It makes sure inherent safety in terms of orbital dynamics. Image of HTV flight path for EDT demonstration is shown in Figure 10.

Hazard-2 is for structural failure of EDT mission components causes hardware to deform or break away and collide with the ISS. Control for Hazard-2 is prevent deform or break away by mechanical design, material and fastener control.

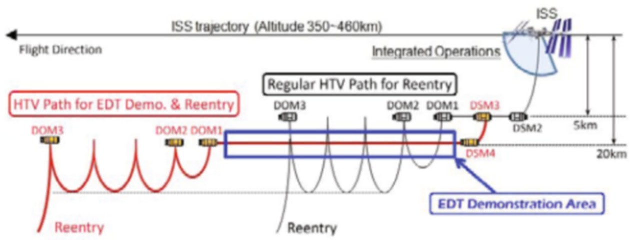

Figure 10 HTV Flight Path for EDT Demonstration

Hazard-3 is for failure of launch lock which causes inadvertent release of end-mass which may cause the physical damage to HTV or ISS hardware. Inadequate commanding system or thermal design is possible cause of this hazard. This type function is called “Must Not Work Function (MNWF)” at safety review. Control for Hazard-3 is applying three independent inhibit for deployment control system. Three independent command decoders, power switches are applied. At mechanical system review, thermal design is also validated.

Hazard-4 is for inadvertent actuating of FECC. inadvertent actuating of FECC may cause the electrical damage to EVA (Extra-vehicular activity) crew or ISS hardware. FECC actuating near ISS is also a MNWF. Control for Hazard-4 is applying three independent inhibit for deployment control system.
Hazard-5 is for sharp edged, pinch point, and etc, which causes injury of EVA crew. Control for Hazard-5 is review design and equipment. Hazard-6 is for extreme equipment temperature by inadequate thermal design, which causes injury of EVA crew. Control for Hazard-6 is review of thermal analysis. Hazard-7 is for electrical shock to EVA crew. Defective component, wire, insulation may result in the electrical shock to crew during emergency EVA. Control for Hazard-7 is applying circuit protection, wire sizing control, bonding, etc.

With the exception of the EVA crew safety requirements (Hazard-4/5/6/7), safety requirements for the ISS can be considered as reliability requirements in the active debris removal mission in the future. For the HTV EDT demo mission, 2 Fault Tolerant (2FT) design is applied since ISS requires it for the ISS safety. Mission cost and reliability requirement for each active debris removal mission would be major consideration to select one of 1FT and 2FT.

9.2 Safety For Reentry

HTV re-entry function is designed to satisfy single fault tolerant requirement of JAXA. Also, since HTV re-entry must be controlled re-entry, tether and end-mass must be removed after experiment to prevent collision to HTV. Therefore, tether cut electronics and mechanism are designed to satisfy single fault tolerant requirement.

10 CONCLUSION

This paper introduced HTV mission design, JAXA’s on-orbit EDT demonstration plan using HTV, development status of EDT demo system and safety consideration of EDT demonstration system.
Hazard analysis for EDT demo system had already finished and design review related ISS safety will be held in late 2014CY or early 2015CY. JAXA almost complete critical design phase for EDT demonstration system on HTV and start manufacturing and test of flight equipment in 2014.
JAXA plans to operate HTV-6 in late 2016CY and conduct JAXA's first on-orbit demonstration of EDT after resupply to the ISS.

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