NASA's Exploration and In-Space Services (NExIS) Division OSAM-1 Propellant Transfer Subsystem Progress 2020

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National Aeronautics and Space Administration (NASA)'s Exploration and In-Space Services (NExIS) Division of Goddard Space Flight Center has been developing technology for the On-orbit Servicing, Assembly and Manufacturing Mission 1 (OSAM-1) to robotically refuel heritage and new satellites on-orbit. OSAM-1, formerly known as Restore-L, successfully passed an important NASA milestone called Key Decision Point-C (KDP-C), receiving agency-level approval for its implementation. The decision point also establishes the mission's official schedule and budget. The OSAM-1 spacecraft, Servicing Payload and the Space Infrastructure Dexterous Robot (SPIDER) payload will refuel a satellite in space, assemble a communications antenna and manufacture a beam. By demonstrating these capabilities, the mission is advancing never-before tested technologies for use in future missions (by NASA and other government organizations and private industry). The mission is funded by the Technology Demonstration Missions program within NASA's Space Technology Mission Directorate.

This paper covers a review of servicing extensibility and critical technologies that are being developed within NExIS with a focus on the fluid transfer refueling technology within the framework of the Propellant Transfer Subsystem (PTS). An overview of the planned initial technology demonstration servicing mission via the OSAM-1 Space Vehicle is provided as an extension of the technology development progress reported in 2018[1], and 2019[2]. The general objectives, challenges, and key technologies are presented as an introduction to the context of the OSAM-1 mission, and a precursor to the OSAM-1 PTS specific development status. Development and progress of the Hose Management Assembly (HMA) and Propellant Transfer Assembly (PTA) are discussed. HMA risk reduction test results including those of thermal vacuum testing are presented. Important analytical results are discussed and progress of drawings and procedures developed for the fabrication and testing phase are shown. A summary of the PTS overall

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verification status and design activities prepared for the critical design peer review are presented. Procurement progress is shown with status on long, medium, and short term efforts to acquire the hardware required to support the mission objectives. Technology development, challenges, and testing status are discussed with particular regard to the OSAM-1 specific key assemblies including the PTA and HMA along with the overall integrated flight mockup of the spacecraft to client fluid transfer testing conducted in the servicing testbeds. The paper concludes with key milestones leading to the goal of on-orbit refueling to be demonstrated in 2024. The overall mission Launch Readiness Date (LRD) has been realigned to accommodate budget profiles and incorporation of additional on-orbit assembly and mnaufacturing demonstration efforts.

Nomenclature

ATP	Acceptance Test Procedure
BSA	Box Subassembly
CAD	Computer-Aided Design
CDR	Critical Design Review
CV	Check Valve
cm/s	Centimeters per Second
ConOps	Concept of Operations
CSA	Clamshell Subassembly
CSV	Cooperative Service Valve
CY	Calendar Year
DOORS	Rational Dynamic Object Oriented Requirements System
eCDR	Engineering Critical Design Review
EEE	Electrical, Electronic, and Electromechanical
EGSE	Electrical Ground Support Equipment
EMI/EMC	Electromagnetic Interference/Electromagnetic Compatibility
ESD	Electrostatic Discharge
ETU	Engineering Test Unit
FDV	Fill and Drain Valve
FLT	Flight
FM	Flow Meter
FMEA	Failure Mode and Effects Analysis
FTS	Fluid Transfer System
GEO	Geosynchronous Earth Orbit
GHe	Gaseous Helium
GOLD	Goddard Open Learning Design
GPM	Global Precipitation Measurement
GSE	Ground Support Equipment
GSFC	Goddard Space Flight Center
HFCS	Hybrid Flight Computing System
HPFT	Hosted Payload, Fluid Transfer
HTSA	Hydrazine Transfer Subassembly
HMA	Hose Management Assembly
HSA	Hose Subassembly
HRT	Hypergol Refueling Tool
I&T	Integration and Test
ICD	Interface Control Document/Drawing
IMS	Integrated Master Schedule

JSC	Johnson Space Center
KSC	Kennedy Space Center
L7	Landsat 7
LV	Latch Valve
LEO	Low Earth Orbit
LNG	Liquefied Natural Gas
LRO	Lunar Reconnaissance Orbiter
LRD	Launch Readiness Date
MEL	Materials and Equipment List
MEOP	Maximum Expected Operating Pressure
MGSE	Mechanical Ground Support Equipment
Mil-Spec	Military Specifications
MMH	Monomethyl hydrazine
N2H4	Hydrazine
NASA	National Aeronautics and Space Administration
NCR	Non-Conformance Report
NExIS	NASA's Exploration and In-Space Services Division
NTO	Nitrogen Tetroxide
OSAM-1	On-Orbit Servicing, Assembly and Manufacturing Mission 1
PDR	Preliminary Design Review
PMD	Propellant Management Device
psia	Pounds per Square Inch Absolute
PSU	Payload Services Unit
PTA	Propellant Transfer Assembly
PTS	Propellant Transfer Subsystem
QD	Quick Disconnect
RDSA	Roller Drive Subassembly
RFA	Request for Action
NExIS	NASA's Exploration & In-Space Services Division
SPIDER	Space Infrastructure Dexterious Robot
SSPD	Satellite Servicing Projects Division
SV	OSAM-1 Space Vehicle
TDMS	Technical Data Management System
TVAC	Thermal Vacuum
U.S.	United States

VTSA	Vent Thruster Subassembly		*WOA*	Work Order Authorization

I. Introduction

ON-orbit propellant transfer between a servicing vehicle and heritage spacecraft is an area of great practical interest, as evident from the studies, development, and testing efforts expended over the past ten years as documented in NASA's Exploration and In-Space Services (NExIS) Division Propellant Transfer Subsystem (PTS) progress[1,2]. The NExIS Division, formally known as the Satellite Servicing Projects Division (SSPD), of NASA's Goddard Space Flight Center (GSFC) is developing technologies for its On-Orbit Servicing, Assembly and Manufacturing Mission 1 (OSAM-1), formally known as Restore-L, to robotically refuel a satellite in orbit. NExIS serves as a focal point for the overall management, coordination, and implementation of on-orbit satellite servicing, assembly, and manufacturing technologies and capabilities for NASA. It also conducts trade studies, carries out demonstrations on-orbit, manages technology development for servicing, assembly, and manufacturing missions, and advises and designs cooperative elements of related space system architecture technologies. The benefits of the satellite refueling technology (both hardware and concepts for operation) being developed are of direct interest to commercial and other government satellite servicing efforts, including start-up industries and component-level aerospace manufacturers.

OSAM-1 mission concepts are being developed to demonstrate and enable capabilities for transferring hypergolic propellant to a spacecraft in LEO, with NExiS targeting in general many heritage operational satellites in GEO and LEO. These heritage satellites were not originally designed for propellant replenishment and have no specific designated on-orbit cooperative "refueling" port. The OSAM-1 Space Vehicle (SV) would supply propellant to a client satellite for mission extension via its existing set of propulsion subsystem ground servicing fill and drain valves, whereas new program architecture designs could incorporate a cooperative servicing valve (quick disconnect). An overview of the specific OSAM-1 Space Vehicle (SV) stack with client is shown in **Figure** 1. This SV is being equipped with conceptual cooperative servicing aids, including servicing valves and servicing interface. The mission architecture consists of three elements: an SV, a Ground Element, and the Launch Vehicle. The SV element is further divided into two main systems: spacecraft bus and Servicing Payload. Additionally, the SPIDER payload (not part of the servicing payload), attached to the spacecraft bus, will demonstrate on-orbit assembly and manufacturing.

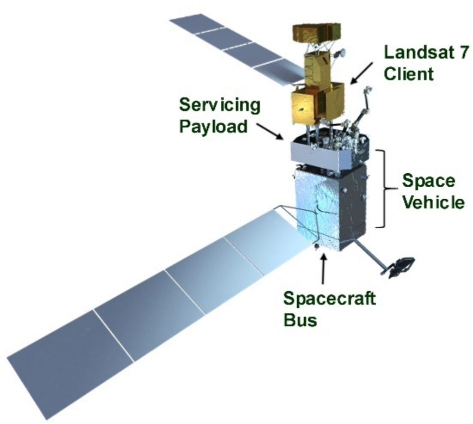

Fig. 1 Servicing satellite concept conducting propellant transfer.

There are five critical technologies being developed for servicing heritage satellites that were never designed to be serviced (**Figure** 2): 1) rendezvous and proximity operation systems, 2) high-speed, fault-tolerant computing, 3) dexterous robotics, 4) robotic tools and tool drives, and 5) fluid transfer systems (FTS). These core technologies are extensible to many space system architectures (**Figure** 3) including government fleet management, commercial enterprise, human exploration, infrastructure inspection and maintenance, asteroid redirection, Artemis Program, Moon to Mars, on-orbit assembly, observatory servicing, planetary defense, propellant depot, and orbital debris mitigation.

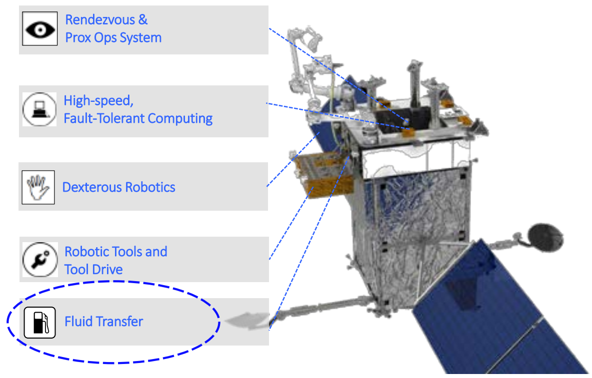

Fig. 2 Critical technologies for satellite servicing.

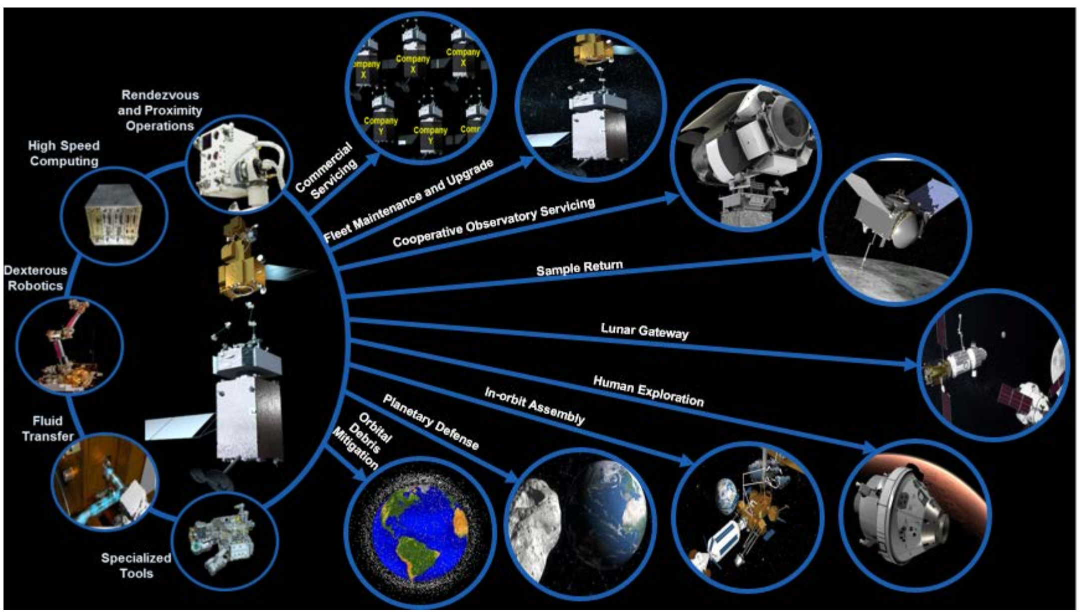

Fig. 3 Representation of servicing extensibility.

This paper primarily focuses on the progress of the fluid transfer technology development connected with satellite refueling in relation to OSAM-1. Status on OSAM-1 PTS development will be presented, including key milestones connected with the on-orbit refueling demonstration, which is scheduled for launch in 2024. Principal challenges and key technology developments with regard to PTS will be discussed, focusing primarily on the recent progress since 2019.

II. Propellant Transfer System

A. General Description

The main objective of the PTS, specifically the Servicing Payload portion of the OSAM-1 PTS, is to safely transfer storable (hypergolic) propellant to a heritage or a newly designed cooperative satellite in orbit. A generic rendering of a satellite servicer spacecraft (like OSAM-1 concepts) and the client satellite is shown in **Figure** 4, highlighting the fluid transfer line robotically connected to the client.

The propellants include reactive and corrosive commodities, namely hydrazine (N2H4) for OSAM-1, with major concepts and hardware extensible to monomethylhydrazine (MMH) and nitrogen tetroxide (NTO) for other missions. Some of the principal challenges of the PTS include on-orbit propellant transfer to non-cooperative heritage spacecraft (not designed for servicing), clients with various mission profiles, residual pressure levels and types of propellant tanks (diaphragm or surface tension type propellant management devices (PMD), and fill and drain valve interfaces (three general designs for United States [U.S.] satellites). The key technologies required to successfully transfer propellant on-orbit are the operational concepts and the associated fluid system architecture. Two key enabling (unique) hardware elements of the architecture are the hose management assembly (HMA) and zero-g precision fluid flow meter. The PTS incorporates a flexible architecture for multi-client servicing and provides some extensibility to other fluid systems (xenon, helium, and cryogens).

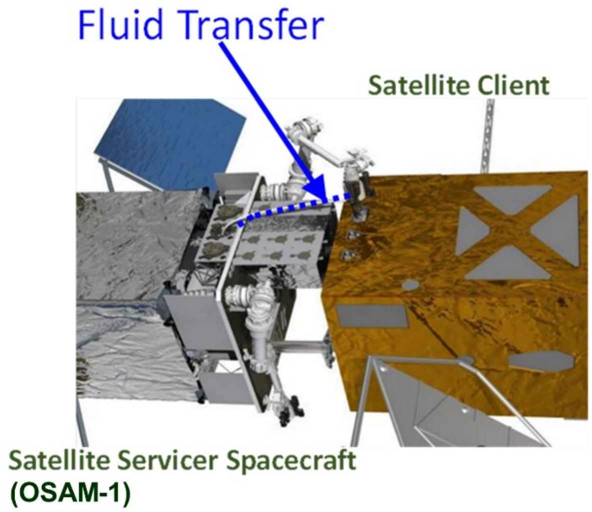

Fig. 4 Propellant transfer system with transfer line highlighted.

Figure 5 illustrates the on-orbit servicing concept of OSAM-1. The Space Vehicle is analogous to the fuel truck that delivers the propellant and provides OSAM-1 with six degree of freedom control. The PTS of the servicing payload contains the HMA and the Propellant Transfer Assembly (PTA). This is analogous to the familiar gas station pumping, metering, and control systems. A Hypergol Refueling Tool (HRT) with a Quick Disconnect (QD) was developed to interface with existing client propulsion systems currently operating on-orbit. This can be likened to a Liquefied Natural Gas (LNG) type automobile refill end effector, but robotically mated. For the OSAM-1 mission, the primary focus is on hydrazine, although the technologies developed are easily extensible to other storable hypergolic propellants.

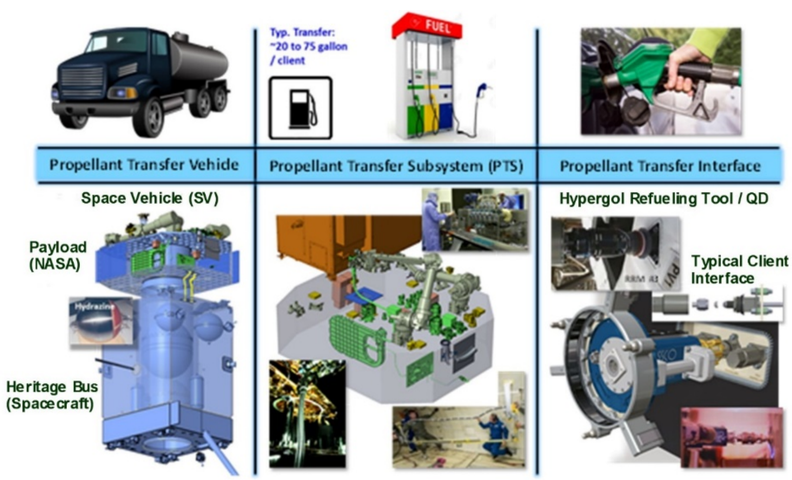

Fig. 5 On-orbit propellant servicing concept.
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B. Basic Architecture

A high-level block diagram visually depicting a generic PTS architecture, shown in **Figure** 6, has had no major architectural changes in the year 2019-2020. The architecture consists of two major sections: the spacecraft bus propulsion and the NASA-developed payload. The FTS is joined at an interface between the tankage and the transfer modules. The spacecraft bus propulsion subsystem houses the propulsion subsystem components including thrusters (for full six degree of freedom vehicle control), tanks, plumbing, valves, valve drivers, etc. for different commodities. The NASA-developed servicing payload section comprisess a propellant transfer assemblies for each commodity, and associated hose management assemblies and nozzle tools that communicate with the client satellites. In future missions, the servicer-to-client interface could be made cooperative assuming cooperative servicing valves are implemented on future spacecraft.

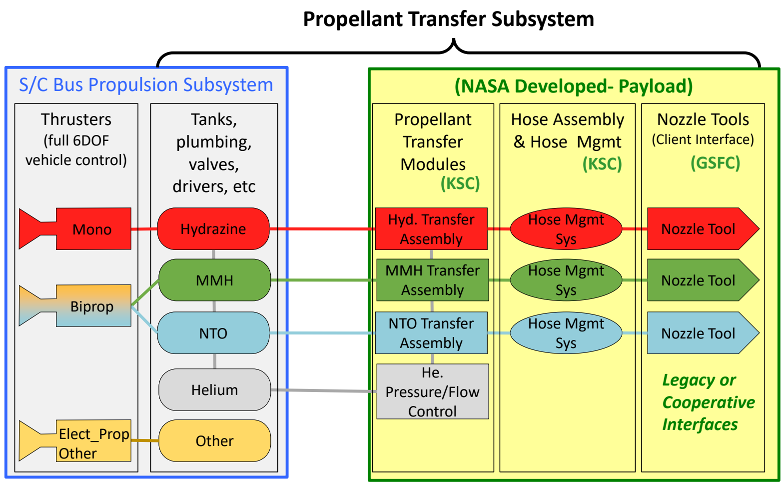


Fig. 6 Propellant transfer system basic architecture.

Most of the progress made on fluid transfer technology within the division was made on the OSAM-1 PTS detailed in Section III below.

III. OSAM-1 PTS ConOps and Architecture

The PTS is being developed for the OSAM-1 Mission that will provide refueling services to a government-owned client satellite located in LEO. This paper focuses on the functional performance, design and verification for the portion of the PTS located on the servicing payload but also includes the spacecraft bus for some analytical summaries.

The PTS transfers propellant safely and reliably from a servicer satellite to a client satellite. It manages pressures, propellant flow, and delivers Mil-Spec propellant (approximately 30 gallons) to Landsat 7 (L7). It also minimizes propellant released to space, maintains the hydrazine within temperature constraints, and performs leak checks within the PTS and the client fluid interface connection. The basic layout of the PTS housed within the servicing payload is shown in **Figure** 7. The PTS consists of two major assemblies, namely the PTA and the HMA, which are further broken down into a total of six subassemblies. The PTA comprises the Hydrazine Transfer Subassembly (HTSA) and the Vent Thruster Subassembly (VTSA), while the HMA includes the Roller-Drive Subassembly (RDSA), Hose Subassembly (HSA), Clamshell Subassembly (CSA), and the Box Subassembly (BSA). This unique Servicing Payload PTS architecture uses slightly modified heritage hardware and technology coupled with safe and efficient detailed conceptual operations.

The PTS design is considered robust and reliable, with proven heritage components extensively tested in new ConOps applications (except for the flow meter and HMA which were evolved from heritage technologies). The pressure (fuel) transfer operations were primarily guided by heritage flight operations demonstrated on the NASA-Johnson Space Center Orbital Refueling System Experiment[3, 4]. The system is designed to refuel an existing client spacecraft and provide the capability for cooperative refueling. In this specific client configuration, the hydrazine and helium are supplied by the spacecraft bus side of the interface to the Servicing Payload PTA.

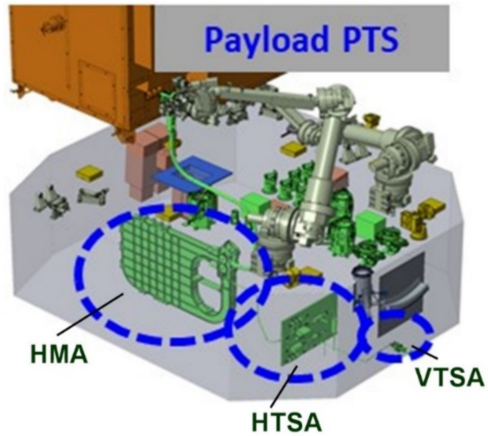


Fig. 7 Propellant Transfer Subsystems positioned within the servicing payload.

IV. Propellant Transfer Subsystem Technology Developments

Figure 8 shows PTS development for OSAM-1. The past year of development effort focused on completing critical design products leading to an engineering critical design peer review (eCDR)[5] held during July 18-19, 2019. These eCDR products (efforts) included the following risk reduction testing:

- Extensive fluids testing to anchor mathematical models for the client interface liquid removal operation via an evacuation venting process
- Simulated client interface leak testing
- Propellant transfer simulations including timing of events of key manifold isolation valve cycles
- HMA engineering test unit (ETU) and controller upgrades that supported the following:
    - HMA thermal vacuum testing
    - 200 abrasion cycle
    - Electromagnetic interference/electromagnetic compatibility (EMI/EMC).

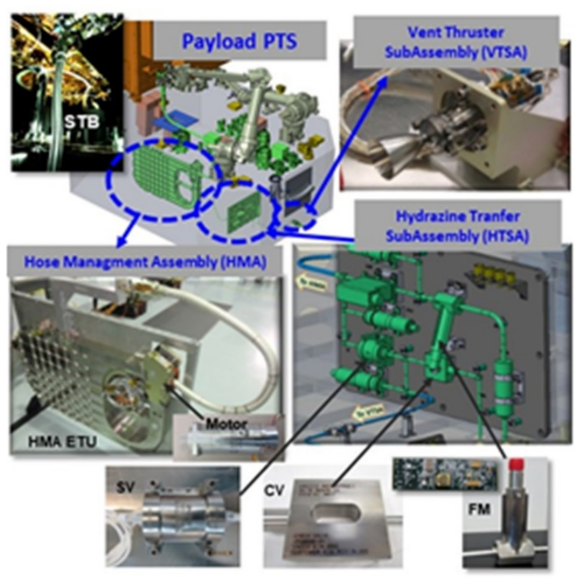


Fig. 8 Propellant transfer subsystems development.

At the time of eCDR, the PTS development progress had achieved a critical design level, and major assemblies and subassemblies with supporting design definition were rigorously tested and showed maturity to the detail design level. A progressive schedule was shown that summarized the PTS-level reviews, subassembly reviews and major long lead component development advancements. Though there was some slip in the schedule with regard to planned activities associated with overall project and budget re-phasing, the PTS did make signifigant progress. At the time of the PTS eCDR, the progress showed an achievable path to the major milestone of the PTS delivery to the OSAM-1 project Integrated Master Schedule (IMS) leading to the servicing payload integration and downstream scheduled tasks. The critical path driver lies in receiving the HRT for integration with the HMA, and similar near critical path receipt of remaining long lead PTS components. Major tests completed after the Preliminary Design Review (PDR) were covered in the eCDR.

Since the eCDR, additional progress was achieved in the PTA and HMA related activities, including flow and pressure drop testing of components (including cavitating venturi characterization), flow analysis, HMA ETU testing, assembly and test procedure generation, the first PTS flight weld on the VTSA, along with acceptance level testing of the VTSA. There was good progress made with in the manufacturing of the long lead components and receipt of medium and shorter lead parts has begun. Work continues on flight assembly and testing for the HTSA and HMA with parallel work efforts and serial completions per the IMS plan. The HTSA drawings have all been released and the manufacturing has begun. Based on present (early 2020) COVID-19 restriction delays, late component integrations, into the HTSA and HMA flight subassemblies are expected to be formally completed with certification by no earlier than May and June 2021 respectively.

The following sections summarize the design development highlights leading to the flight PTS fabrication and testing campaign.

A. Propellant Transfer Assembly

1. *Hydrazine Transfer Subassembly*

The HTSA major components are as follows: Propellant filter, latch valve (LV), check valve (CV), solenoid valve, pressure transducers (PT), flow meter (FM), and gas orifice. The key functions of the HTSA are:

1) Isolate hydrazine supplied from the spacecraft
2) Measure hydrazine flow rate (and totalized transfer mass after hybrid flight computing system (HFCS) processing)
3) provides an interface for gaseous helium (GHe) needed for client fluid interface leak check
4) provides an interface between the HMA and VTSA needed to depressurize and evacuate propellant manifolds (including client interface).

Technical progress in some of the areas related to HTSA has been previously reported[6-10].

The drawings, ICDs, procedures, reference documents, analyses and controls were developed. The master equipment list for the HTSA showed positive weight margin as required at the detailed level of development. Lessons learned, NCRs, waivers, and open requirement verification items were documented. The weld plan and acceptance testing plan were developed. Associated ground support equipment (GSE) and electrical ground support equipment (EGSE) development recorded good progress and is on track to support the flight unit assembly and planned testing.

The HTSA design was reported to be mature and ready to begin fabrication following the approval of several open Technical Data Management System (TDMS) documents and drawings, receipt of the long lead components, and completion of the necessary work order authorizations (WOAs). The HTSA design has been fully analyzed and tested to ensure expected performance during the mission, with minor revisions possible (minor schedule slack available to HTSA fabrication start) based on eCDR actions and any continued test results such as orifice adjustments.

In support of the HTSA design and development, several key tests were performed with supporting analysis. **Figure** 9 displays a photographic view of the water test setup used for the investigation of depressurization and evacuation of water from the transfer system, showing the small volume and large volume regions[10]. Major typical transfer subsystem component locations are shown. The large volume is about 25 times larger than the small volume. This test setup yielded the dispersion characteristics (initial burst due to pressure differential, and a subsequent slow discharge due to evaporation) of the large volume and the small volume, which were satisfactorily correlated with analysis. Reference 10 presents further applicable related details of this testing efforts, results, and conclusions.

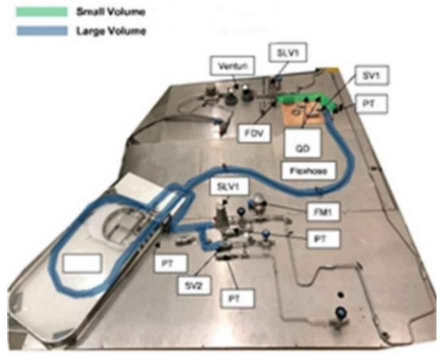
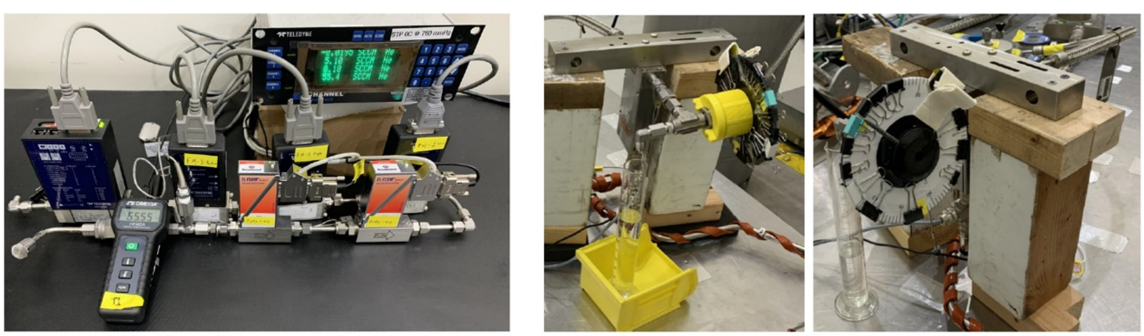


Fig. 9 Photographic view of the water evacuation test setup.

Another major effort, undertaken with regard to flow rate and pressure drop measurements, was completed with the aid of water flow testing. The maximum flow rate is controlled by a cavitating venturi, and the pressure drop in each of the PTS components was measured and correlated as a function of the flow rate. The performance of the venturi in both the cavitaitng and non-cavitating modes has been characterized, and compared with existing test data for water. **Figure** 10 shows a photograph of the water flow test setup. The water test data was scaled to hydrazine flow for flight application.

Fig. 10 Photographic view of the water flow and pressure drop test setup.

Expanding on the past work on GHe leak check investigations[9] (test and analysis) relating to on-orbit leak test of the interface, additional investigations were carried out to determine equivalent water leak rates for a known GHe leak rate for arbitrary leak sizes. **Figure** 11 presents the leak test setups for GHe and water for an arbitrary leak sizes with the aid of needle valve custom caliper dial mechanism. The measurements were correlated with analytical models over a wide range of precision GHe and water leak flow rates for typical credible hypergol components and mechanical connections. This data establishes the leak detection range of the PTS design and leads to the development of client interface leak rate requirements. The water leak rate data could be scaled to hydrazine for flight application.



(a) GHe leak flow test setup. **(b) Water leak flow test setup.**

Fig. 11 Photographic view of the GHe and water leak flow test setups

2. *Vent Thruster Subassembly*

The VTSA comprises a heritage monpropellant thruster with electrical and mechanical mounting brackets. The key function of the VTSA is to allow GHe and N2H4 / GHe mixtures to be vented to space as part of nominal and off-nominal ConOps.

The heritage thruster is a flight spare unit from the Global Precipitation Measurement (GPM) mission. There is extensive flight heritage for thew thruster including GPM and the Lunar Reconnaissance Orbiter (LRO). The VTSA has series-redundant single seat solenoid valves and an electrical bracket with four electrical connectors (primary/secondary power, primary/secondary signal) that interface with the servicing payload harness. Performance information for the thruster was shown to meet all of the PTS unique vent disposal requirements.

The master equipment list for the VTSA showed positive weight margin as required at the detailed level of development. Lessons learned, NCRs, waivers, and open requirement verification items were documented. All documents, flight hardware, and GSE required for VTSA fabrication and subassembly-level testing were released and ready to support the start of fabrication and acceoptance test efforts.

Fabrication of the VTSA at the GSFC Code 597 propulsion work center was carried out. The weld plan and the acceptance testing implementation were completed by February 2020. Supporting GSE and EGSE development showed good progress and is on track to support the final integrated payload flight unit assembly and testing planned.

The first PTS flight weld that was completed on the VTSA is shown below in **Fig.** 12. Overall VTSA assembly and testing was completed in February 2020 pending the final EIDP and Certification reviewupcoming.

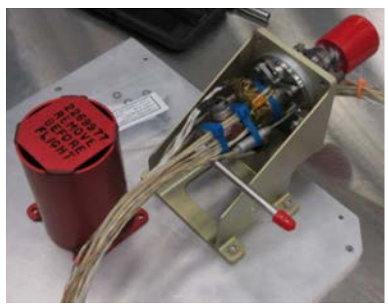


Fig. 12 PTS VTSA Weld.

B. Hose Management Assembly

The key functions of the HMA, comprising RDSA, HSA, CSA, and BSA, are: 1) allow PTS to transfer hydrazine propellant to client as part of nominal ConOps, 2) maintain fuel at required temperature range in both full shadow and full sunlight, and 3) deploy and retract (stow) the flexible refueling hose in a controlled manner, and 4) interface with HTSA and HRT. An image of the HMA ETU (cover removed) with labels is shown in **Figure** 13.

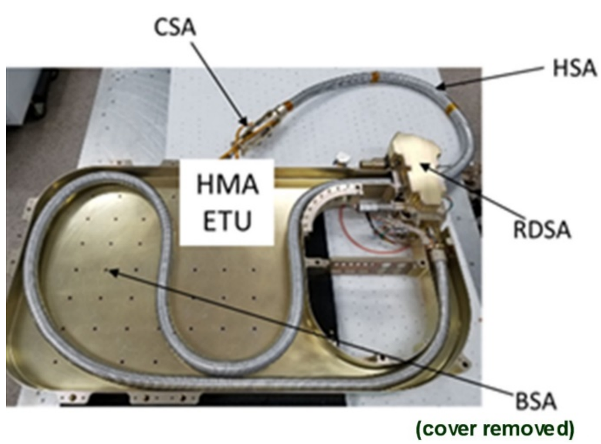


Fig. 13 HMA ETU (cover removed) with labels.

The RDSA is designed per NASA-STD-5017, Design and Development Requirements, and includes a pin puller which allows contingency roller drive release (no single-point failure). It permits variable HSA slow controlled travel rates of 0.2 or 0.5 cm/s, via a heritage flight motor drive (a procurement).

The HSA is designed and qualified for all environments, and has integrated heaters and temperature sensors which were electromagnetic interference (EMI) tested in August 2017 (which led to a 28 VDC filter being added) for no impacts to accurate thermal monitoring and control. It includes thermal coating protection for full sun exposure with hydrazine contained within. The coated conduit was abrasion tested in October 2018, and thermal properties analysis updated in August 2017. The inner annealed stainless steel convoluted hose was 100% radiographically examined and verified to the meet the 5x operating pressure burst rating following testing to the worst case hose torque that will be seen in flight. The hose was also verifed to meet the performance requirements for hundreds of allowable twist, torque, and bend radius cycles. These uniquely developed specialty inner flex hose qualification tests along with internal precision cleanliness processing certification were completed in June 2019 by a heritage aerospace hose manufacturer under a NASA development contract. Flight unit certified hoses were received in December, 2019.

The CSA houses the pressure transducer and the solenoid valve, the critical weight and size of which were validated at the manufacturer pre-fabrication review. The pressure measurement error is shown to be less than 3% (component and avionics), thus achieving detection capability for the HRT to fill drain valve (FDV) connection leak rate of $1x10^{-2}$ sccs GHe (or better), i.e. one order of magnitude better than visual detection capability.

Qualification-level vibe/shock testing was completed in April, 2018 to validate the analysis and design. The ETU HMA vibration tests were completed in August, 2018. The BSA has maximum deflection of approximately 0.15" under 3 sigma launch loads protecting the hose, and has a high factor of safety (FS) to yield. It has a removable cover, and vent holes for controlling the launch ascent depressurization rate. The BSA size was optimized to enable storage of a connecting hose for multiple clients who may have different requirements.

The drawings, ICDs, procedures, reference documents, analyses controls, were documented. Several highlights related to the ETU risk reduction test campaign included completing the launch survivability vibration risk reduction test, the ascent vent risk reduction test, Thermal-Vacuum (TVAC) chamber testing, abrasion tests, and EMI/EMC testing.

1. *HMA Motion Operations*

The HMA motion conceptual operations were investigated. Moving the HRT is a cooperative process between the robot team and PTS with alternating movements of the HSA and the robot arm to predetermined trajectory way points for specifc client interface needs. High margins to movement were incorporated to prevent any HSA damage such that precision accuray of waypoint stops are not required (except for minimum hose deployment confirmation before the next robotic arm motion). At no point will the robotic arm and RDSA motor operate at the same time. During the flight operations, the SV operator commands the HMA motor to either extend or retract the HSA depending on next planned robotic arm position based on PTS team inputs. PTS then visually verifies will verify the HSA displacement. Following the hose waypoint movement, the vision subsystem provides lighting and exposure adjustment of views allowing conduit ink marks (**Figure** 14) to be identified using situational awarness cameras to verify that the desired hose position was acheived. The HFCS and PSU teams provide the control input to the brushless direct current motor on the HMA to spin the RDSA rollers for a specific time and speed. The ConOps are similar for retraction.

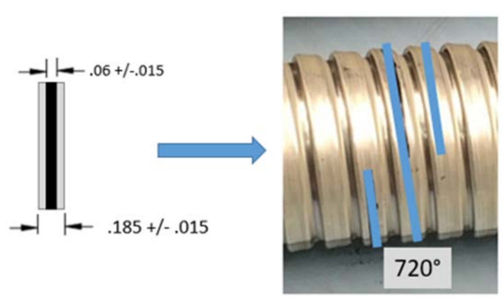


Fig. 14 HSA conduit ink marking (720°).

Test results from lights out demonstrations in the GSFC Robotic Operations Center validated the conceptual operations. The demonstrations were considered sufficient to show that engineering prototypes of the subsystem assemblies working together in a systematic trajectory-based maneuver method succesfully achieved the goals and objectives of the operation to maneuver the HRT with the HSA and robotic arm attached to the Landsat 7 work site (FDV area) where refueling operations are requried. Visual indications were consistent with what was expected and defined in the test objectives.

An image of the vision subsystem situational awareness view of the HSA is shown below in **Figure** 15. The HSA is shown on the left side of the image coming from the HMA and goes to the top center where it interfaces with the CSA and HRT. A mockup of Landsat 7 is in the background and appears golden in color due to the thermal blankets that are on the exterior of the mockup. Note that the flight hardware is designed to accommodate multiple clients with different interface valve positions, and requires unique ConOps way point planning for each client. HMA demonstration testing for other typical clients is also ongoing under a separate generic study program called FuSeD (Future Serviceability Demo), which is funded by sources other than the OSAM-1 mission with expected completion by end of CY 2020.

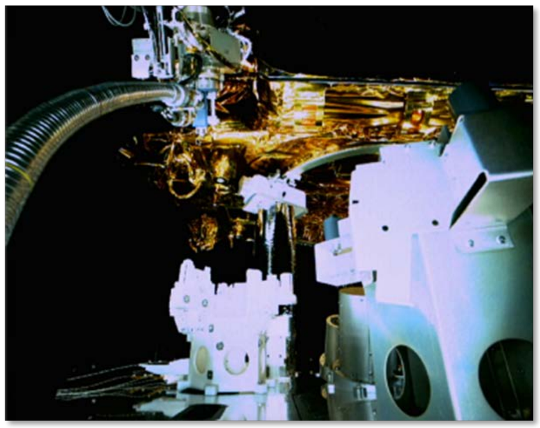


Fig. 15 Vision subsystem situational awareness camera view of the HSA.

2. *HMA Vibration Testing*

Figure 16 presents an image of the vibration test setup. All components performed nominally with functional checks verified against performance parameters pre- and post- test.

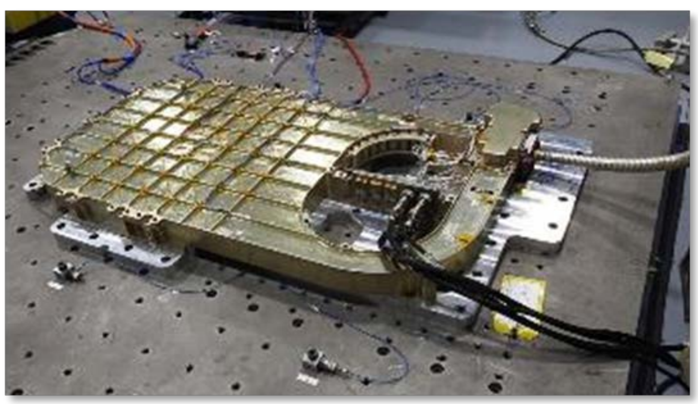


Fig. 16 HMA ETU Launch Survivability Vibration Risk Reduction Test setup.

3. *HMA Ascent Vent Testing*

An image of the Ascent Vent ETU Risk Reduction test setup is displayed in **Fig.** 17. All components performed nominally. No noticeable change in the mechanical characteristics were identified for the approximately 4 meter HSA after the test and before and after thermal vacuum (TVAC) of a 1-m reference HSA verified no change in required range of thermal performance.

Fig. 17 Ascent Vent ETU Risk Reduction Test setup.

3. *HMA ETU Thermal and Abrasion Cycle Testing*

The HMA ETU was disassembled and a harder coat finish coupled with minor surface contours was applied to HSA surfaces within the BSA to reduce chances from any possible contamination from abrasion of any potential contact surfaces. An updated flight-like HSA with flight-like ETU internal flexible hose was fabricated to support integration into the HMA ETU. The HMA ETU was assembled and the acompanying controller was built to facilitate risk reduction testing of the HMA. The ETU thermal and abrasion cycle testing was performed to evaluate the mechanical performance of the RDSA's ability to deploy and retract the HSA (motor activation), performance of the RDSA's contingency release mechanism (pin puller activation), performance of the HSA thermal conduit coating, and evaluate performance of the BSA hardened coating.

The HMA ETU was subjected to Thermal Vacuum (TVAC) testing (in December 2019) at qualification levels for 12 cold and hot cycles followed by 50 HSA abrasion cycles (see **Figure** 18). The test was conducted at GSFC building 7, Facility 239. The objectives of this ETU risk reduction level test were to perform functional testing of the HMA ETU's components, particularly the RDSA, after thermal soaking at each cold and hot cycle and to evaluate the performance of new enhanced BSA (hardened) coating and RDSA roller guides to minimize abrasion-induced contamination. This testing was followed in January, 2020 by an additional 150 informational extensibility abrasion cycles at ambient temperature and pressure for RDSA evaulation. Once the cycle testing was completed, powered and unpowered pull testing of the HSA was performed to confirm RDSA drive margin in excess of factor of two.

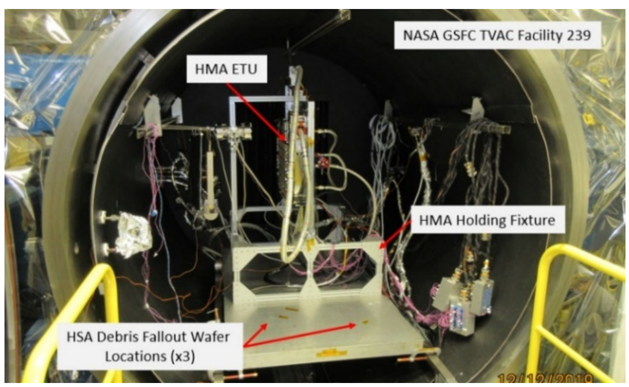


Fig. 18 HMA ETU during TVAC and HSA Abrasion Cycle Testing.

The successful execution of the testing validated the HSA conduit and BSA coating design and the RDSA's ability to provide nearly slip-free motion of the hose. Analysis of the particulates generated during the extended cycle testing (exceeded the cycles needed for OSAM-1) and provided some higher levels of cycle contamination data useful for future mission planning and possible extended life cycle design moifications to certain piece parts that come into contact with each other.

While the HMA ETU testing campaign was in process, the team was also starting pathfinder pedigree machined parts work including demonstrations of dimensional certification at the KSC prototype shop. This work was in preparation of flight hardware processing planned throughout 2020 for the HMA mechanical parts. A large perecentage of flight HMA parts were completed, but some remain due to the work COVID-19 work stoppage restrictions in March 2020.

4. *HMA HSA EMI/EMC Testing*

Following the completion of TVAC and Abrasion Cycle testing at GSFC, the HMA HSA underwent EMI/EMC testing at the KSC Electromagnetics (EMI) Laboratory (Chamber 1) in February 2020 (**Figure** 19). The EMI/EMC test evaluated the HMA HSA performance when subjected to the EMI/EMC environments as specified by the expected OSAM-1 mission environment, and specifically addressed gaps in the initial HMA prototype EMI/EMC testing completed previously. All EMI/EMC tests have been performed to validate the HSA hose design and identify any design changes needed before final integration into the next higher level assembly. Testing was implemented according to the OSAM-1 requirements established in the control plan using MIL-STD-461F, MIL-STD-461C, MIL-STD-462, and GSFC-STD-7000A test methods. Tests included inrush current, radiated susceptibility (RS103), conducted susceptibility (CS02), radiated emissions (RE102), and differential mode emissions (CE03). The successful completion of this test validated the updated HSA design. The HMA ETU complied with the requirements and verified the new EMI filter, thus paving the way for the fabrication of the HMA ProtoFlight Unit (PFU). Overall the HMA testing campain and progress with flight pedigree parts controls is maturing steadily and on track to support protoflight manufacturing, integration and testing in 2021.

Fig. 19 HMA ETU during EMI / EMC Testing (RE102 Test shown).

The master equipment list for weight allocations for the HMA showed positive margin as required at the detailed level of development. Work was completed to minimize the mass of the CSA, attached to the robotic arm. Lessons learned, NCRs, waivers, and open requirement verification items were documented. Updated drawings were prepared with the design layout and planned integration to the servicing payload. Fabrication of the majority of the HMA ETU subassemblies was carried out at KSC with the CSA final assembly, including the solenoid valve and pressure transducer, being welded/integrated at the GSFC Code 597 propulsion work center. Similar collaborative KSC/GSFC fabrication tasks for the flight unit to be tested at protoflight levels are presently being serial released under work authorations to the specific shops with all ETU rsik reduction test lessons learned incorporated. The flight hardware weld plan and the acceptance testing plan were developed. All planned and required risk reduction testing preceeding the HMA PFU build have been successfully completed, with fabrication of flight components underway. Machining, assembly and testing work have started; however, are presently on-hold (early 2020) until KSC and GSFC centers re-open due to the COVID-19 restrictions.

V. Propellant Transfer Subsystem Requirements Verification

The design of the propellant transfer subsystem for the servicing payload was defined by the Level 4 OSAM-1 Servicing Payload Propellant Transfer Subsystem Requirements, RL-PTS-REQ-0013 as depicted in the OSAM-1 Mission Requirements Tree, RL-SYS-TREE-0001. Tankage and helium distribution systems situated on the spacecraft side of the interface between the spacecraft and the servicing payload form part of the spacecraft requirements flow down provided directly by the spacecraft supplier, MAXAR.

The Level 4 Servicing Payload PTS requirements had been derived from higher-level requirements and had been linked with parent requirements in the Rational Object Oriented Requirements System (DOORS). Level 5 - 7 PTS requirements dealing with assembly, subassembly and component level efforts were at CDR level or better. Level 5 and 6 drawings were at CDR level, with computer-aided design (CAD) models completed and flight drawings placed in TDMS with many of them released and reviewed at subassembly-level table top reviews. Long lead component procurement documents were released, with many long lead components in final assembly and testing phases, and some received.

There were a few configuration control board (CCB) approved changes post PDR. For example, the maximum propellant spillage allowed when the HRT disconnects from the client FDV after refueling was updated to trace vapor levels. The PTS flow down included hydrazine exposure requirement and functional requirement to vent hydrazine in the stacked configuration to minimize hydrazine release when the HRT is disconnected from QD left on client.

A requirements and verification tabulation was conducted to summarize the PTS requirement set and provide status to date (see Tables 1a-1c). Table 1a shows the total number of PTS requriements and the verification events that were completed at the time of the eCDR. Out of the 166 (check) requirements defined at that time, 65 (check) of them had the verification activities completed. Table 1b shows a summary of the PTS verification methods associated with each requirement, and Table 1c shows a summary of the specific verification data products. Overall, the PTS team achieved good progress with regard to the release of the specific data products. A detailed review of the requirement set was presented with the specific, title, requirement text, ID, verification method, event and approach/plan.

Table 1a.PTS Level 4 requirement summary.

Requirement Type	Number of Reqs	Verification Events Complete*
Functions and Performance	53	39
System Interfaces	17	15
Design Constraints	31	0
Operational Factors	20	0
Safety	11	3
Product Assurance	34	8
Total Reqs:	**166**	**65**
*PTS event documentation in TDMS, final verification approval in-work		

Table 1b. PTS Level 4 verification summary.

Verification Method	Number of Reqs
Analysis	45
Demonstration	9
Inspection	138
Test	45

Table 1c. PTS Level 4 method summary.

Verification Method	Number of Doc/Drawings	Number of Released Doc/Drawings
Analysis	18	10
Demonstration	7	5
Inspection	62	31
Test	26	3

A verification plan was developed, and follows the mission systems engineering process including NPR 7123.1B and GPR 7123.1B the OSAM-1 Mission Systems Engineering Management Plan (SEMP), RL-SYS-PLAN-0003. A flow chart was prepared indicating the steps for verification activities and how those items will be tracked in the configuration management system of the OSAM-1 project and within DOORS. **Figure** 20 shows the verification burndown plan (presented at the CDR) that set the expectations for how and when the verification of the activities would be completed with milestone events serving as the drivers including the Mission CDR, completion of the HMA build, payload handover, and some of the requirements that are anticipated to be verified after payload integration.

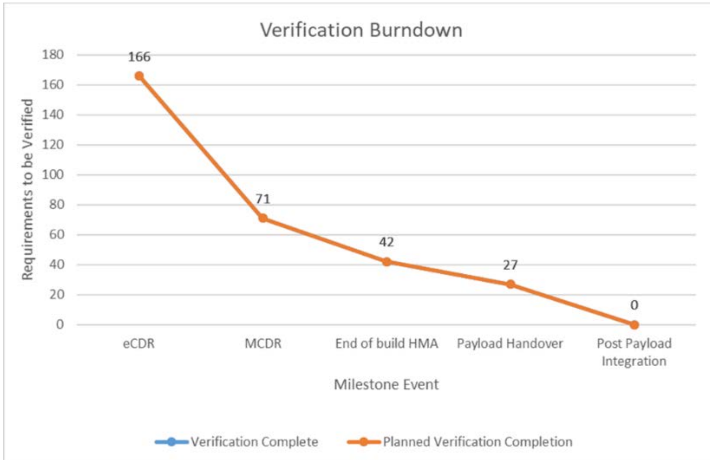


Fig. 20 PTS Verification burndown.

At the completion the PTS assembly fabrication and testing, a serial incremental hardware acceptance review of each subassembly (VTSA, HTSA and HMA) is planned and follows the Baseline Acceptance Review Process and checklists defined in RL-SYS-PLAN-0064 Propellant Transfer Subsystem Integration into Servicing Payload. Present expected phased reviews will occur from early CY 2021 to summer of 2021 based on present projections (without consideration for further COVID-19 restrictions at KSC and GSFC).

The PTS requirement verification plan was updated and shows detailed verification methods, events, and specific plans for each PTS requirement. Pathfinder draft verification evidence cover memorandums have been generated for several requirements and the verification process has started on all items that can be closed prior to mission CDR. All of the verification events are documented and auditable in the configuration managed TDMS and tracked in DOORS.

VI. Propellant Transfer Subsystem Integration into Servicing Payload

Good progress was indicated in the area of payload level integration and testing documentation. **Figure** 21 presents the PTS integration and test flow through servicing payload handover to SV.

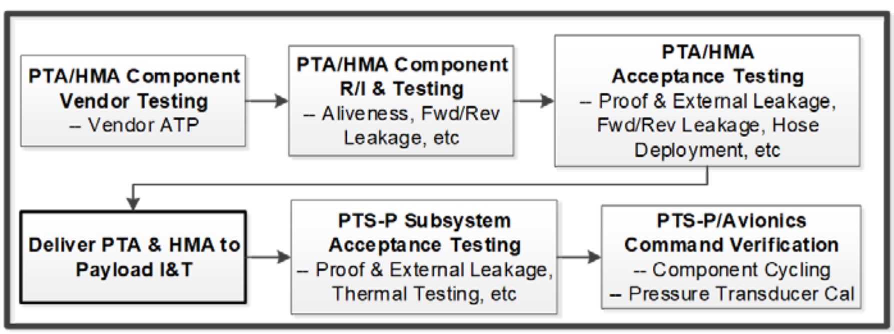


Fig. 21 PTS integration and test flow through servicing payload handover to SV.

During the PTS servicing payload integration, the PTS assemblies will be welded together and tested. Weld head and x-ray device clearances were checked and verified to the designed manifold standoff height. **Figure** 22 shows the fully assembled PTS as it would mount to the servicing payload with the payload structure (hidden for clarity). The VTSA is also shown with the protective cover planned to be used during the integration and test campaign to protect it from accidental damage.

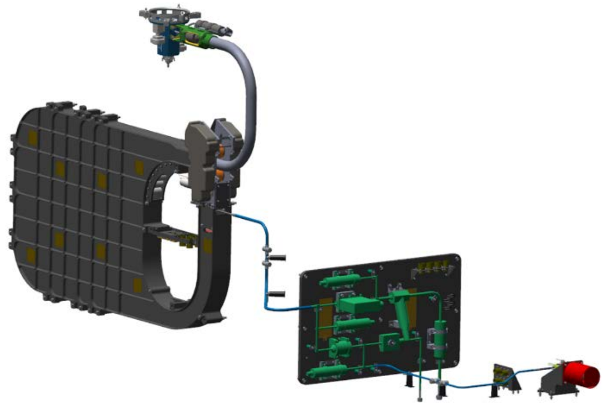


Fig. 22 Integrated PTS at the servicing payload level.

Interconnecting lines structural analysis was carried out, and the acceptance testing was documented including the procedure for the electrical mate to flight avionics. All telemetry will be checked, valves cycled, pin puller actuated, and the hose will be deployed and retracted. A special reset procedure was developed for the pin puller and some additional detail of tools and ConOps documented because of the complexity of the operation. Process controls for the PTS I&T phase were prepared, along with the GSE and EGSE required to support the operations, and facilities shown mapped to the associated PTS I&T work that is planned in each.

In summary, PTS servicing payload I&T activities are considered well understood, and weld plans show no clearance issues for weld head nor x-ray device. As part of the electrical design, results of a derating analysis was shown and the PTS electrical components assessed included connectors, heaters, pressure transducers, solenoid valves, flow meter, EMI filters, platinum resistance thermometers, wire and cable, latch valve, HMA motor, and pin puller. No flight waivers are anticipated for the EEE limited life items analyzed. A risk summary showed all PTS risks in Mantis (mission risk database) mitigated to green or closed, and any remaining residual items designated as highly unlikely risks have been acknowledged, being tracked for certification pedigree of as-built items. The acknowledged risks are related to single point failures documented in both the PTA and the HMA. The risks have been accepted as highly unlikely as documented in two engineering memorandums summarizing the risks and resolution by robust design, test margins, and conceptual operational backup means.

Major changes and trades since the PDR were reported in two categories, namely, ConOps changes and trades. The ConOps changes comprised the following:

1. The pressures across the client FDV is no longer fully balanced before valve opening.
2. Initial L7 priming sequence will be performed with OSAM-1 N2H4 tanks at launch pressure (lower than nominal transfer pressure) to protect against excessive adiabatic compression in the L7 lines; once L7 manifolds are wetted (primed), SV N2H4 tanks will be pressurized to nominal transfer pressure.
3. Prior to disconnecting from the L7 FDV, based on water correlated to N2H4 tests, PTS will vent/evacuate the transfer manifolds through the VTSA to minimize the N2H4 volume released upon disconnect.

The trades included the following:

1. A decision was made to rely on software inhibits for PTS component actuations in lieu of enable plugs (HMA pin puller is the sole exception).
2. Selection of reliable and proven mechnical payload to SV interface line connection type was chosen and ordered, along with backup connector.
3. A decision was made to rely on vision cameras to detect N2H4 leakage while flowing rather than qualify and implement a leakage detection device such as a derivative of an ammonia detector (similar to the one used on the ISS).

The propellant transfer methodology showed PTS and HFCS are developing a transfer script that enables on-board calculation of mass flow rate and mass totalization. The on-board transfer script stops flow when a limit (transfer duration, mass totalization, or max pressure) is reached or a fault is detected. If the flow meter or totalizer fails, the backup plan will utilize discrete commands sent from the ground to flow for conservative time durations. Transferred mass will be estimated on the ground while flow is stopped (prior to restarting).

Good progress was shown in the area of SV-level integration and testing documentation and the general flow was presented in **Figure** 23.

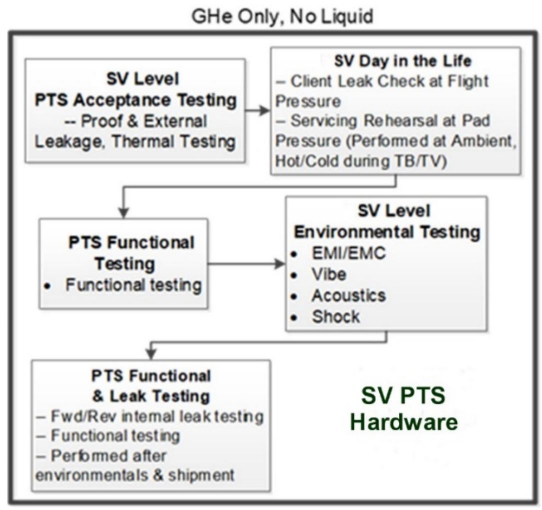


Fig. 23 PTS integration and test flow through SV.

The activities through launch site operations along with supporting ground support equipment (GSE) and electrical ground support equipment (EGSE) were documented. Some of the historical testing activities include pressure surge testing and evacuation testing conducted at KSC with ETU functional simulators. Propellant and power budgets were updated. Similar to the interconnecting lines on the servicing payload, the stress analysis for lines from the servicing payload to the spacecraft was completed. Fault management and software requriements were summarized along with the data rates and budget. The driving requirements for the integrated PTS are fully addressed, and validation and verification activities have been defined. PTS has baselined I&T activities from subassembly through the SV-level, with ongoing discussions with Systems and I&T to determine feasibility of certain limited PTS ConOps demonstrations during environmental testing with GHe flow. Extensive analysis and testing have been performed on the integrated PTS design showing positive margins/test results. The PTS propellant transfer methodology (both primary and backup methods) enables a high-accuracy, low-risk operation. The PTS reliability analysis was conducted per the OSAM-1 mission assurance requirements and critical items were identified. PTS-specific range safety compliance documentation was produced. Overall the integrated PTS at the SV level showed good progress and maturity.

VII. Miscellaneous Activities

A. Integrated Master Schedule

The IMS is updated monthly at a minimum with the details of the tasks required to fully carry out the scope of work required to implement the PTS into the mission plan, and the earned value management system is used to track the progress.

B. Materials and Equipment List

The PTS Materials and Equipment List (MEL) is also updated monthly at a minimum. CAD and ETU weights were reconciled and input into the OSAM-1 master MEL now refined for ETU and some flight component acuracy levels. The PTS continues to exceed expectations of current best estimates with regard to overall mass allocation, and design phase mass margins are being met. For example, the HMA ETU weight was recorded prior the 12-cycle TVAC test in mid-December and included in the MEL update.

B. Long Lead Component Procurement

Major progress was achieved on the long lead procurements required to support the ETU test and flight hardware integration of the PTS. The list of long lead components is as follows: flexhose*, flow meter, pressure transducer, solenoid valve*, check valve*, latch valve, pin puller, motor*, heaters*, resistance temperature detectors (RTDs)*, and mechanical fittings. Those desiganted with an *asterisk* have been received with full EIDP contract certifications and records. The flexhose and flow meter reflect unique designs for OSAM-1, whereas other components pertain to heritage proven designs and suppliers with test qualification verified with the OSAM-1 mission parameters.

The flexhose production qualification testing and flight unit fabrication was completed in January of 2020, and flight units have been received. Flow meter development was met with some initial challenges with regard to manufacturing techniques for internal GFE electronics board rated for all space environments. Flight unit fabriaction is now complete and showing excellent calibration accuracy curve results for required flow rate ranges viscosities before and after environmental testing at varying. Delivery is pending a final EMI acceptance test, final cleaning and approval of the EIDP packages. The flow meter ETU and flight units are on track to meet the required delivery schedule to support ground COnOps testing and flight assembly integration needs. All other heritage long leads are also on track to meet the present realigned mission integration schedule need dates. Some minor fabrication and test delays have caused some early risk reduction ETU flight testbed delays to the original plan.

Along with the long lead parts procurement progress, medium or shorter lead time parts were ordered and some received. This medium lead time procurement progress ensures hardware availability during the flight fabrication phase and solidifies many mechanical and electrical subassembly interfaces. These procurements include both flight and supporting critical GSE, as well as any critical flight development and test contractor support services.

C. Servicing Testbed Support

The PTS team continued to support the systems level testing in the servicing testbed though relatively little work has been done in this area since the eCDR due to some configuration changes that are in-work in the testing facility. The PTS team is preparing to upgrade the PTS hardware that is in the servicing testbed. This work is scheduled in the late 2020 time frame to support system level testing with critical ConOps flight ETU level pedigree components from the same flight production line incorporated into the servicing testbed at GSFC such as for the HMA, flow meter, latch valve, and pressure transducer.

Overall, the OSAM-1 PTS is progressing within present IMS milestones and plans toward flight. There remain final fabrication, integration and tests planned along with qualification/verification testing that is scheduled for completion through servicing payload integration starting in (no earlier than) mid-calendar year (CY) 2021. The PTS architecture and conceptual operations were optimized with OSAM-1 spacecraft and both the spacecraft and PTS completed critical design reviews. Long lead component procurements are all in progress with most nearing completion. Payload level I&T is scheduled to start NET mid-CY 2021 followed by SV I&T with a launch readiness date to follow in CY 2024 timeframe. Note that continued COVID-19 work restrictions could create further schedule realignments.

VIII. Summary

Fluid transfer system development is progressing as planned within NExIS to support OSAM-1. NExIS on-orbit fluid transfer technology development and test efforts performed from 2011 to date are applicable to assist related potential commercial, government, and/or other U.S. space-related endeavors. Key intellectual property from test and analysis efforts may be applied to various clients and multiple fluid commodities. Initial in-flight technology demonstrations are focused on hydrazine transfer in accordance with OSAM-1 mission specific requirements. Functionality, safety, and reliability are not only based on design technology and physical architectures utilized but are highly dependent on intellectual knowledge concerning ConOps and controls unique to particular clients. The OSAM-1 and generic PTS technologies under development are largely extensible to other NASA goals including advanced pre-staged depot/servicer, Artemis Program architectures, human landing system (HLS), refueling of Mars/other deep space missions, and enable servicing from derived in-situ propellants. Examples of the NExIS Fluid Transfer Hardware Technology, which is available and cataloged, include the following: Propellant Transfer Assembly, Hose Management Assembly, Zero-g Fluid Flow Metering, and Cooperative Service Valves. Applications for further information may be requested by U.S. companies or interested parties by contacting the representative listed below under the header NASA Satellite Servicing Technology Catalog.

IX. Conclusions

NASA's Exploration and In-Space Services (NExIS) Division of Goddard Space Flight Center in collaboration with Kennedy Space Center continue to lead the development of technology to robotically refuel a satellite on-orbit demonstrating one of the key objectives in its overall OSAM-1 mission effort (restoration of heritage on-orbit satellites, extending their or other similar client productive operable use via demostration of on-rbit refueling technologies and ConOps). Several key technologies relating to the propellant transfer system have been developed, and partially and fully tested, and demonstrated, as discussed in this paper (with full on-orbit mission demonstration in CY2024),

Acknowledgments

This work was funded by NASA GSFC NExIS under the OSAM-1 Project. Thanks are extended to the entire PTS team, including several members who contributed in the past to the OSAM-1 development.

References

[1] Coll, G. T., Webster, G. K., Espinosa M. R., Aranyos, T. J., Nufer, B. M., Valle, J. B., and Kandula, M., "Satellite Servicing Projects Division and Restore-L Propellant Transfer Subsystem Progress," AIAA-2018-4942, 2018.

[2] Coll, G. T., Webster, G. K., Pankiewicz, O. K., Schlee K. L., Aranyos, T. J., Nufer, B. M., Valle, J. B., Tamasy G. J., and Kandula, M., "Satellite Servicing Projects Division and Restore-L Propellant Transfer Subsystem Progress," AIAA-2019-4435, 2019.

[3] Boyd, W.C., Orbital Refueling System STS 41-G Quick-Look Report, Propulsion and Power Division, NASA Lyndon B. Johnson Space Center, October 1984.

[4] Griffin, J., NASA-JSC ORS (Orbital Refueling System) Experiment, NASA/USAF Interchange on Spacecraft Maintenance, October 1-2, 1985.

[5] Propellant Transfer Subsystem (PTS) Engineering Critical Design Review (eCDR), RL-PTS-REVW-0201, July 18-19, 2019 (EAR 9E515 / ITAR protected, requiring US company requests through GSFC NExIS technologies office for release of redacted copy without any supporting company proprietary information).

[6] Espinosa, M.R., Webster, G.K., Coll, G.T., Nufer, B.M., Kandula, M., and Aranyos, T.J., Internal Depressurization of Hydrazine with Application to In-Orbit Satellite Refueling," AIAA-2018-3913, 2018.

[7] Kandula, M., and Nufer, B. M., "Characteristic Pressure Rise with Temperature Increase in Liquid-Locked Hydrazine Systems for Satellite Refueling," AIAA-2018-3912, 2018.

[8] Webster, G. K., Coll, G. T., Kandula, M., and Nufer, B. M., and Aranyos, T.J., "Compressibility Effects on the Discharge Coefficient of Small Diameter Ratio Sharp-Edged Orifices with and without Downstream Chamfer," AIAA-2019-3651, 2019.

[9] Kandula, M., Nufer, B. M., Felt A. M., Hicks, N. G., Aranyos T. J., Webster, G. K., and Coll, G. T., "Compressibility, Reynolds Number and Thermal Effects in Pressure-Decay Based Leak Detection Systems," AIAA-2019-3437, 2019.

[10] Kandula, M., Nufer, B.M., Hicks, N.G., Aranyos, T.J., Webster, G.K., and Coll, G.T., "External depressurization and evacuation of water from a typical transfer subsystem," AIAA-2020-3036, 2020.

NASA Satellite Servicing Technology Catalog

NASA has compiled this technology catalog to support the direct transfer of a rolling portfolio of on-orbit servicing, assembly and manufacturing (OSAM-1) technologies (hardware and software) through commercial licenses and/or other agreements, such as software usage agreements. Various NASA field centers including Goddard Space Flight Center (GSFC) Exploration & In-Space Services Division (NExIS), Langley Research Center (LaRC), and Marshall Space Flight Center (MSFC) will assist with this transfer of technology to industry, universities, other Government Agencies, and non-governmental organizations. To learn more about the NASA Technology Transfer Program and how it facilitates collaborations between NASA researchers and external parties for mutual benefit, visit https://technology.nasa.gov/network. To arrange further technical discussion of specific on-orbit servicing technologies, contact Tammy Brown (301-286-5753; tammy.l.brown@nasa.gov) of GSFC, Danette Allen (757.864.7364; danette.allen@nasa.gov) of LaRC, or Jeramie Broadway (256.961.1372; jeramie.w.broadway@nasa.gov) of MSFC.

This catalog describes the capabilities and maturities of technologies developed or being developed, specifies the environments for which the various technologies will be qualified, any New Technology Reports (NTRs) or patents issued for the technology, and overall target timeframe for technology maturity. Note that the suite of in-space manufacturing technologies are at a nascent state of maturity. Accordingly you will not find individual manufacturing technologies listed by name in this release of the catalog. That will change in the future as technologies mature.

OSAM-1 technologies fall into the following groups:

- Relative Navigation System: Sensor suite (visible, infrared, lidar), Rendezvous and Proximity Operations algorithms (range, bearing, pose)
- Reconfigurable Avionics & Software: SpaceCube^{TM} processor, Video Distribution & Storage Unit
- Robot System: NASA Servicing Arm, Robot Electronics Unit (REU), robot flight software
- Tools and Mating Systems: Advanced Tool Drive System, sophisticated servicing tools (gripper, blanket cutter, wire cutter, cap removal, & nozzle tool) and adapters, astronaut tools
- Fluid Transfer System: Propellant Transfer Assembly, zero-g fluid flow meter, hose management system, seal-less pumps and associated intellectual property of overall subsystem development
- Cooperative Servicing Aids: Rendezvous decals, Cooperative Service Valve
- In-space Assembly: Resident space object inspection, life extension and anomaly recovery, persistent platforms, very large observatories, human exploration of the Moon and Mars, lunar surface excavation and construction, sample collection and return from near-earth objects, orbital debris mitigation/remediation, etc.
- In-space Manufacturing: Cutting, joining and machining processes, manufacturing process, in-process inspection, repair, verification and validation, material manipulation for manufacturing