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FIRST FLIGHT OF RAFTI ORBITAL REFUELING INTERFACE

Abstract

This paper presents data and results from the first flight of Orbit Fab's Rapidly Attachable Fluid Transfer Interface (RAFTI). The RAFTI service valve is a drop-in replacement for existing spacecraft fill/drain valves and enables in-orbit grappling/attachment and fuel transfer. The development of a robust orbital propellant supply chain is critical to accelerating the growth of government and commercial space activities. Widespread availability of spacecraft refueling has the potential to provide a number of revolutionary benefits. Existing high-value space assets could have their operational lives extended, as they will no longer be constrained by running out of propellant for maneuvering, and on-orbit servicing missions would become more efficient as servicing vehicles can be repeatedly reused after refueling between missions. A large orbital propellant supply would also enable cheaper mobility for spacecraft, allowing new missions and business models based on operational flexibility and frequent maneuvering. RAFTI is a key enabler for refueling as it provides a reliable interface for fuel transfer.

The RAFTI architecture has three main components. The RAFTI Service Valve (SV), which is the primary subject of this paper, serves as a passive fill/drain and orbital refueling valve. It is complemented by the RAFTI Space Coupling Half (SCH), which is a combined fluid transfer interface and grapple feature that attaches to the RAFTI service valve in space to enable fuel transfer, and the RAFTI Ground Coupling Half (GCH), which is used for ground fueling. The RAFTI SV is flying for the first time aboard Orbit Fab's Tanker 001 Tenzing spacecraft. Launching no earlier than June 1 2021, Tenzing is the world's first orbital propellant tanker and a testbed for key orbital refueling technologies. Tenzing is a 35 kg small satellite with a bus provided by Astro Digital carrying a supply of storable monopropellant, High Test Peroxide (HTP). Tenzing carries two RAFTI service valves, one for the spacecraft's primary propellant storage tank and one for the spacecraft's propulsion system. This paper presents information on RAFTI, it's role in the Tenzing mission architecture, and data showing RAFTI's performance from flight and pre-flight testing.

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First Flight of RAFTI Orbital Refueling Interface

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Abstract

This paper presents an overview of Orbit Fab's Rapidly Attachable Fluid Transfer Interface (RAFTI) and results from its first flight aboard the Tanker-001 Tenzing Mission. The RAFTI service valve is a replacement for existing spacecraft fill/drain valves and enables in-orbit grappling/attachment and fuel transfer. The development of a robust orbital propellant supply chain is critical to accelerating the growth of government and commercial space activities. Widespread availability of spacecraft refueling has the potential to provide a number of revolutionary benefits. Existing high-value space assets could have their operational lives extended, as they will no longer be constrained by running out of propellant for maneuvering, and on-orbit servicing missions would become more efficient as servicing vehicles can be repeatedly reused after refueling between missions. A large orbital propellant supply would also enable cheaper mobility for spacecraft, allowing new missions and business models based on operational flexibility and frequent maneuvering. RAFTI is a key enabler for refueling as it provides a reliable interface for fuel transfer.

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Keywords: Refueling, RPOD

Acronyms/Abbreviations

CONFERS Consortium for Execution of Rendezvous and Servicing Operations.

GEO geostationary Earth orbit.
GSE ground support equipment.

HTP high-test peroxide.

IPA isopropyl alcohol.
ISS International Space Station.
ISSNL International Space Station National Lab.

LEO low Earth orbit.

RAFTI Rapidly Attachable Fluid Transfer Interface.
RGC RAFTI Ground Coupling.
RPOD rendezvous, proximity operations, and docking.

RSV RAFTI Service Valve.

SCH RAFTI Space Coupling Half.

1. Introduction

Limited fuel supplies present a significant constraint for current spacecraft, limiting them to single use lifetimes and restricting operations which require high levels of mobility and significant propellant expenditures. The ability to refuel spacecraft at all scales on orbit and at various locations will fundamentally change astronautics and enable new missions and applications [1], [2], [3]. Refueling in space is not a new concept, having been proposed for use in various mission concepts since the earliest days of spaceflight [4]. However, implementation of refueling has thus far been limited by financial, technical and logistical challenges. Orbit Fab is overcoming these challenges and building a widespread orbital refueling infrastructure. By developing a network of

Fig. 1. Render of Tenzing's exterior including the spacecraft's two RAFTI interfaces and fidcucials

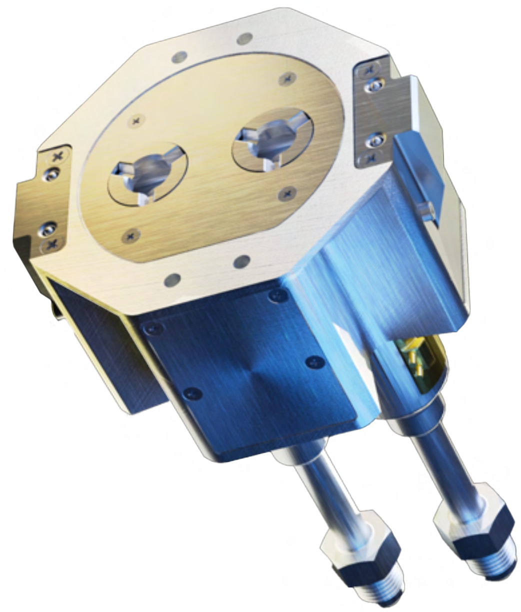

Fig. 2. Render of the latest version of the RAFTI Service Valve

tankers and proliferating systems to support refueling in space, Orbit Fab is changing the paradigm for space missions by enabling reusability and previously unachievable levels of mobility and operational flexibility. Widespread availability of fuel in orbit will reshape the next generation of missions and jumpstart the development of a bustling economy in space.

Orbit Fab has taken the first big leap with the Tanker-001 Tenzing mission (shown in fig. 1). Tenzing is the first of many propellant depots Orbit Fab is developing. Tenzing builds upon Orbit Fab's Project Furphy which demonstrated fluid transfer on the International Space Station (ISS)[5]. On Tenzing, Orbit Fab leverages smallsat economics to fly a functioning on-orbit tanker while also flying an orbital testbed with risk reduction and technology development payloads for future missions.

1.1 RAFTI

Orbit Fab's Rapidly Attachable Fluid Transfer Interface (RAFTI), flying for the first time on the Tenzing Mission, is one of the key technologies enabling orbital refueling. The RAFTI architecture consists of the RAFTI Service Valve (RSV), RAFTI Ground Coupling (RGC), and RAFTI Space Coupling Half (SCH). The RSV is a replacement for typical spacecraft fill/drain valves used in ground fueling operations that is designed to enable on-orbit refueling by incorporating the necessary features for grappling and fluid connection in the space environment. The latest version of the RSV is shown in fig. 2. RAFTI is compatible with a variety of propellants and fluids. This paper primarily focuses on using RAFTI with high-test peroxide (HTP) as that is the propellant used on the Tenzing Mission. Tenzing carries two RSVs, one connected to the primary propellant tank and one connected to the propellant tank of the spacecraft's Halcyon propulsion system developed by Benchmark Space Systems. The RGC was used in conjunction with the service valves to fill these tanks in ground fueling operations. This mission marks the first flight demonstration of the RSV.

1.2 High-Test Peroxide

The fuel used on Tanker-001 Tenzing, High-Test Peroxide (HTP), may seem unconventional but actually has a rich history of Aerospace applications. Due to modern understanding and manufacturing, HTP is gaining prevalence as a non-toxic, safe, high-performance alternative to other long duration propellants such as Hydrazine. This non-toxicity makes it incredibly range safe, allowing it to easily launch from many possible locations, and more easily be implemented in various satellite designs. High-Test Peroxide can also be derived directly from water, making it the only high-impulse storable monopropellant and oxidizer that can be created from Lunar Resources. With so many non-toxic, high performance HTP propulsion systems being developed and its great potential not only for refueling now, but in future In-Situ Resource Utilization architectures that Orbit Fab is planning to support, HTP provides a great fit for this

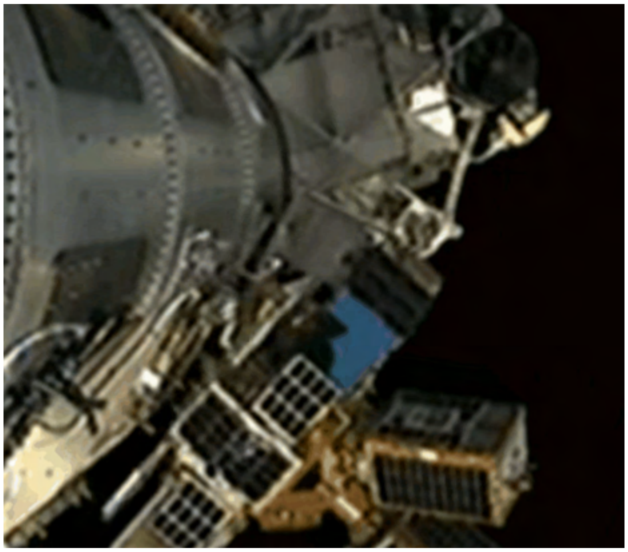

Fig. 3. Tenzing in view as Sherpa LTE-1 deploys from Transporter-2 (Image Credit: SpaceX Transporter 2 Stream)

first flight of RAFTI and the refueling architecture while advancing understanding for future missions.

1.3 Tenzing Mission Overview

Orbit Fab developed the Tanker-001 Tenzing Mission as both the world's first propellant tanker and an orbital test-bed for key technologies to enable on-orbit refueling. The mission was developed on an aggressive timetable with less than nine months between project kickoff and launch. Orbit Fab's payloads on the Tenzing mission include the primary tank system storing HTP, RAFTI, fiducial markers to facilitate alignment during proximity operations and docking, and an imaging system developed in partnership with SCOUT Inc. On future missions, these cameras and fiducials will serve as the core of a fully cooperative and prepared rendezvous, proximity operations, and docking (RPOD) system for in-space refueling enabling spacecraft to approach for docking using RSV and SCH. Tenzing also includes a Halcyon Propulsion System from Benchmark Space Systems which was also fueled using RAFTI and will be used to test rendezvous and proximity operations maneuvers. The spacecraft's bus was provided by Astrodigital. Tenzing launched on June 30th, 2021 on Space X's Transporter-2 mission as a rideshare payload on Spaceflight Inc.'s Sherpa LTE-1 (fig. 3) orbital transfer vehicle and deployed successfully several hours after launch. Since launch, Tenzing has successfully begun operations and verified nominal propellant storage in the primary tank system. A more detailed general overview of the Tenzing mission can be found in a paper published earlier this year at the 35th Annual Small Satellite Conference[6].

This paper provides an overview of the first flight of RAFTI on the Tenzing Mission. Section 2 provides an overview of the RAFTI architecture and the development process used for RAFTI. Section 3 details the ground testing campaign used to verify RAFTI's readiness for flight. Section 4 outlines the ground fueling campaign for the Tenzing spacecraft at Cape Canaveral Space Force Station using RAFTI. Next, Section 5 presents initial results from flight. Section 6 then outlines the new RAFTI Block 2 design incorporating lessons learned from ground fueling and flight. Lastly, Section 7 provides concluding remarks and next steps for Orbit Fab and the RAFTI Program.

2. RAFTI

2.1 Development Process

The development of RAFTI began with the formulation of requirements gathered from over 30 industry groups including US government agencies, US domestic corporations, international corporations, industry standards, specifications and industry best practice groups such as (CONFERS). From the feedback these groups provided on features, requirements, and expected performance, Orbit Fab developed the RAFTI architecture. It was determined early in the process that a successful in-space refueling interface should also function as a fill/drain valve or service valve for initial fueling of the spacecraft on the ground. Analysis of the requirements for these two phases of operation determined that while the refueling interface could be designed to support both use cases, the fundamental requirements for the ground coupling and space coupling diverged. This lead to the development of a common service valve for ground and space operation, but the development of separate mating couplings to operate in the ground and space environments.

With this analysis of the requirement space, Orbit Fab derived the principal requirement governing RAFTI development: the system for connection of the two spacecraft on-orbit should be the same system as the propellant transfer system. That is, RAFTI must be capable of supporting direct docking applications for spacecraft, reducing the need for a robotic arm and hence significantly reducing the cost and complexity of the system.

While this requirement drives the design of a new refueling system for spacecraft which prioritize refueling ability at all stages from concept to flight, there are many space assets which may not be able to support this operation mode. RAFTI therefore also supports secondary connection on systems where the interface is not trusted due to heritage concerns, the RPOD system doesn't have sufficient precision, or on underactuated spacecraft. This last case is of particular interest, which would enable the refueling of uncontrolled spacecraft or the gathering of fuel from inactive tankers.

From the requirements phase, a series of trades and prototype examinations were undertaken, evaluating technologies including cam locks, nested annular propellant ports, and magnetic attachment. Indeed, Orbit Fab flew a magnetic attachment system to the ISS as a demonstration aboard

Project Furphy TODO: cite furphy from ISS RnD conf. via the International Space Station National Lab (ISSNL) and tested this method of attachment. While the mechanism was solid, concerns on insufficient misalignment tolerance, bounce after impact in the microgravity environment and the general impact of the powerful magnetic fields on other spacecraft systems led the team to examine other avenues.

This resulted in the multi-finger grasp and dual interchangeable valve core configuration shared by all RAFTI blocks. Following the development of a prototype, RAFTI was announced at the Cube Sat Developers Workshop in 2019[7]. Since the public announcement of RAFTI, a range of companies from propulsion providers to satellite operators have expressed interest in incorporating RAFTI as an element of their system, and it has been sold to six customers for integration into their spacecraft.

In order to allow rapid iteration and reduce risk, a Block 0 variant of the RAFTI valve core was developed which only supports use as a fill drain valve for ground fueling operation. Performance requirements for RAFTI Block 0 were defined in order for the coupling system to be competitive against commercially available fill and drain valves in the market at the time of development. These performance requirements are summarized in table I.

Parameter	Low Pressure RSV
Max Operating Pressure	500 psig
Proof Pressure	750 psig
Burst Pressure	1250 psig
Docking Misalignment	±10 mm (X, Y)
	±10° (X, Y, Z)
Mated External Leakage	1×10^{-6} scc/s
Unmated Internal Leakage	1×10^{-6} scc/s
Cycle Life	$\geq$ 1.000 cycles
Operating Temp Range	–40 °C to 120 °C
Weight (grams)	500 g (RSV)
Size	0.25 U (RSV)
Launch Environmental Loads	NASA GEVs
Expected Compliance	NASA GSFC 8009
	AFSPCMAN 91-710

TABLE I
SUMMARY OF THE OVERALL RAFTI BLOCK 0 SYSTEMS EXPECTED PERFORMANCE

2.2 Block 0 Functional and Qualification Testing

Once the Block 0 design was completed prototype units were fabricated and used for functional and qualification testing. Block 0 qualification was intended as a learning exercise for valve design, hardware manufacturing and integration as well as validating the performance of the sealing design. RSV and RGC Block 0 were both designed as direct-acting pintle valves with a threaded O-ring boss fitting serving as the fluid interface to both customer propulsion systems and to ground support equipment (GSE) for fueling operations. The valve housing for both contained either single or dual O-rings captured in a dovetail groove design which when mated provided three inhibits against leakage from the internal propellant flow path overboard in compliance with range safety specification AFSPCMAN 91-710. The three face-sealing O-rings are compressed via a triangular 3 bolt joint along the valve body mounting flange of the RSV and RGC.

Fig. 4. RAFTI Block 0, unmated

Following the mechanical assembly and integration of the Block 0 valve hardware, two assembled RSVs and RGCs were sent out for radiographic inspection. The non-destructive evaluation consisted of a X-ray inspection of valve internals per ASTM E1742/E1742M-18. The test goal was verification of proper installation and evaluation of possible damage to the internal soft-good components in the assembled mated and unmated configurations.

After X-ray inspections, the two RSV and RGC mated assemblies were shipped out for the qualification test campaign consisting of both mated and unmated helium leak, flow characterization, cleanliness verification and destructive burst pressure tests.

Once the prototyping phase was completed, Orbit Fab developed the first flight qualified variant of RAFTI. This version is compatible with newspace customers looking for a single cutoff that could be coupled with thruster run valves in order to provide the appropriate amount of inhibits to meet range safety requirements as defined by AFSPCMAN 91-710 and GSFC 8009.

2.3 Evolution to Block 1

Following the qualification test campaign on the Block 0 valve cores, a Block 1 RSV with two valve cores located side by side within a grapple fixture was developed. This topology closely matched the prototype topology but with improvements for enhanced grasp envelope and design updates for manufacturing considerations and debris mitigation. The first propellant selected to validate the Block 1 RSV was HTP. High-test peroxide has been undergoing a renaissance recently, seeing increased use amongst microspace, newspace

Fig. 5. RAFTI Block 1, unmated

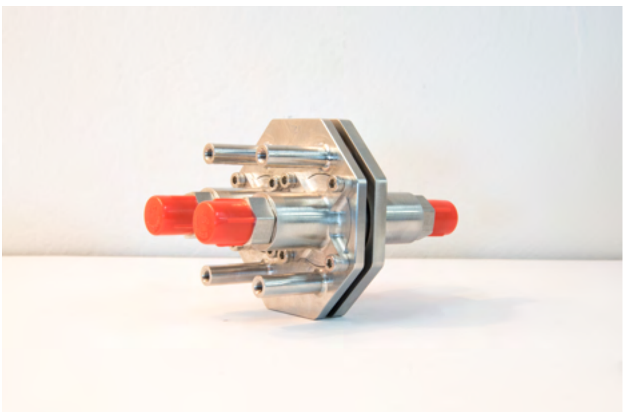

Fig. 6. RAFTI Block 1, mated

Parameter	Low Pressure RSV
Max Operating Pressure	500 psig
Proof Pressure	1000 psig
Burst Pressure	1500 psig
Docking Misalignment	±10 mm (X, Y) ±10° (X, Y, Z)
Mated External Leakage	1×10^{-6} scc/s
Unmated Internal Leakage	1×10^{-6} scc/s
Cycle Life	≥ 1,000 cycles
Operating Temp Range	–40 °C to 120 °C
Survival Temp Range	–80 °C to 120 °C
Weight	200 g (RSV)
Size	60 mm dia. by 45 mm height
Launch Environmental Loads	NASA GEVs
Expected Compliance	NASA GSFC 8009 AFSPCMAN 91-710

TABLE II
SUMMARY OF THE OVERALL RAFTI BLOCK 1 SYSTEM EXPECTED PERFORMANCE

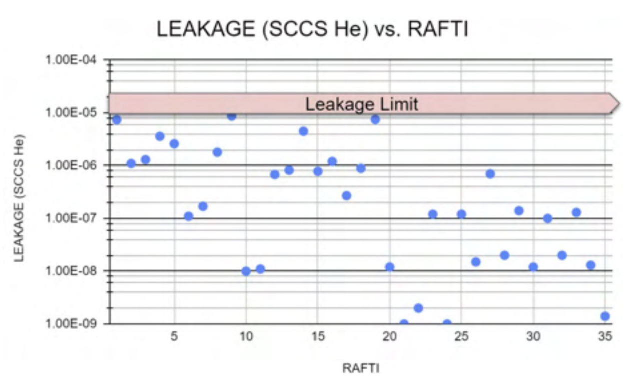

Fig. 7. Helium Leak test data for RAFTI Block 1

and even large space companies, including Benchmark Space Systems, Nimble Aerospace, Orbit Fab, and Sierra Space.

The Block 1 RAFTI's performance characteristics are listed in table II. Block 1 is able to utilise the qualification data from Block 0 as the materials, topology and processes do not differ on the valve cores from Block 0. Only the mounting holes are changed. Additional batches of RAFTI Block 1 hardware were ordered and built up in-house at updated Orbit Fab facilities. Leakage testing was part of the functional test campaign, the data on each unit was recorded and used to evaluate the quality of the build environment and processes in place. Data on leakage performance and variability is provided as reference in fig. 7.

3. Ground Testing Campaign

Following the build and test campaign completed in-house, RAFTI Block 1 valves were sent out to a test house for an acceptance test campaign to qualify them for flight on the Tenzing mission. The tests conducted reflected the previous test campaign for RAFTI Block 0 valves. The flight qualification test campaign consisted of Shock, Random Vibration, Thermal Cycle, Helium Leak, Proof, Burst in addition to functional tests. The levels of each of these tests, the requirements which drove them and the final result are provided in the section/table below.

Flow Characterization

Test Description: Water flowed through assembled RSV-RGC. Inlet pressure and flowrate measured. Outlet pressure is ambient.

Test Goal: Characterize flow performance of RAFTI Block 0 across mated interface and experimentally derive flow coefficient.

Cleanliness Verification

Test Description: The assembled RSV-RGC is flushed with isopropyl alcohol (IPA). IPA is then used to verify cleanliness levels. The parts are dried to remove residual IPA with a filtered nitrogen purge.

Test Goal: To provide parts that are verified clean to the customer as well as characterize cleanliness of in-house build and variability.

Test Requirement: AIAA S-080A §5.1.12

Success Criteria: IEST-STD-CC1256E level 100 R1

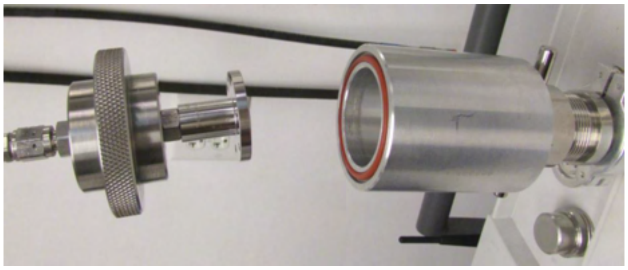

Fig. 8. Helium Leak test of RAFTI Block 0, unmated

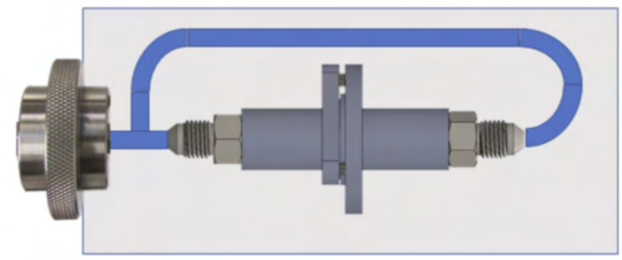

Fig. 9. Helium Leak test of RAFTI Block 0, mated

Helium Leak

Test Description: Non-destructive test performed in the mated and unmated configurations, pressurized with low (30 psia) and high (500 psia) pressure helium. Figures 8 and 9 outline the test configuration used.

Test Goal: To verify proper installation and check for proper function of the internal soft-good components in the mated and unmated configurations.

Test Requirement: AIAA S-080A §10.4.7

Success Criteria: Helium leakage less than 1×10^{-6} scc/s

Data: Shown in Figure 7.

Vibration

Test Description: Evaluate RAFTI Block 0 structural design subjected to random vibration environment from launch.

Test Goal: Verify robust valve design and check for proper function before and after vibration test.

Test Requirement: NASA-GSFC-STD-7000A

Success Criteria: Functional verification.

Shock

Test Description: Evaluate RAFTI Block 0 structural design subjected to shock environment from launch.

Test Goal: Verify robust valve design and check for proper function before and after shock test.

Test Requirement: NASA-GSFC-STD-7000A

Success Criteria: Functional verification.

Thermal Cycle

Test Description: Evaluate RAFTI Block 0.

Test Goal: Verify robust valve design and performance after exposure to temperature extremes.

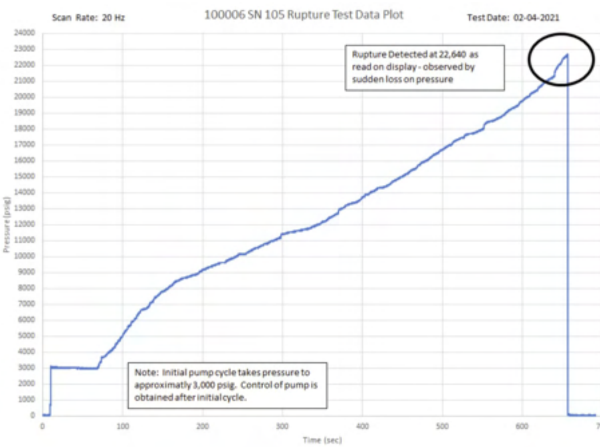

Fig. 10. Burst test data of RAFTI Block 0

Test Requirement: Qualification at 6 cycles, 1 hour dwell, ramp rate 3 °C/min, −61 °C to 120 °C.

Success Criteria: Functional verification.

Burst

Test Description: Unit hydrostatically pressurized to proof, then design burst pressure, then to failure.

Test Goal: Verify valve can survive to the design burst pressure, 2.5x the operating pressure

Test Requirement: AIAA S-080A §5.2.1

Success Criteria: Unit shall survive burst pressure at $\geq 2.5\times$ MEOP (1250 psig)

Data: Shown in Figure 10.

4. Spacecraft Fueling

4.1 Fueling Procedure

After the completion of the qualification testing campaign, the two RAFTI Service Valve Block 1s for the primary tank system and Halcyon propulsion system were integrated with the Tenzing spacecraft. They were then used alongside RGC as the interface to GSE for fill and drain operations. Both propulsion systems on the Tenzing spacecraft were fueled with 90 % hydrogen peroxide, and the system thus had to meet all requirements for hazardous operations. Both propulsion systems used diaphragm tanks, allowing the use of a common set of GSE configured to perform a vacuum fill of the tanks. All wetted surfaces of the GSE and RAFTI were designed and built to ensure material compatibility with HTP. Particular attention was paid to ensure that trapped inter-seal volumes have appropriate bleed paths to mitigate effects of autogenous pressurization of the HTP.

Both propulsion systems propellant and pressurant lines to one core of their respective RSV, and each RSV was then mounted on an external panel of the spacecraft. For ground fueling, the RGC was mounted to the RSV via four captive screws. The fluid connection is created by direct acting pintles on either valve, opened by the action of clamping the

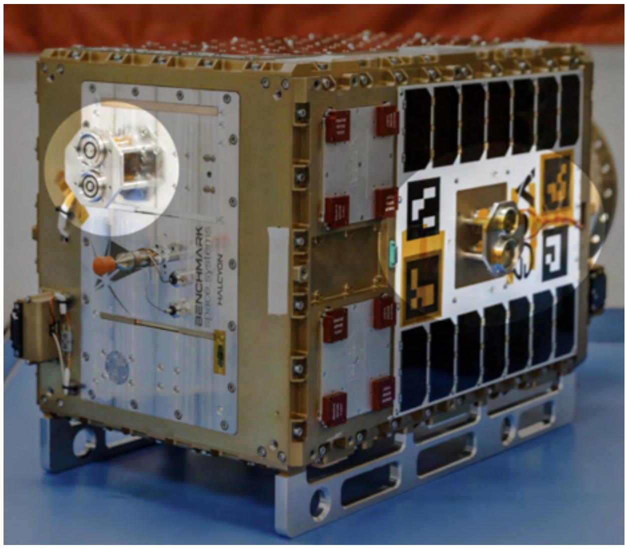

Fig. 11. RAFTI Block 1 Service Valves installed on Tenzing spacecraft

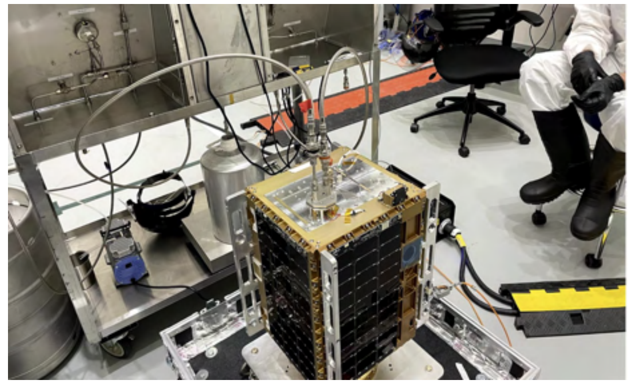

Fig. 12. Tenzing spacecraft with fill cart GSE lines installed

RSV and RGC with the screws. At this point, the remaining GSE from the fill cart was connected to the RAFTI interface via the compression fitting on each RGC port.

At this point the fully-connected fluid system went through a series of leak checks to verify seal integrity. The integrated system is divided into a gas and liquid half and leak checks were performed one side at a time. A vacuum pump was connected to the gas half, and the internal system volume was pumped down to below –26 in Hg. At this point, a hand valve was closed upstream of the vacuum pump and the gas half of the system was isolated. System pressure was monitored for an extended period of time and the leak check passed if the pressure did not exceed –26 in Hg. The same procedure was used to check integrity of the liquid half of the propulsion system.

Once the system passed the leak check, we proceeded to prime the system for fueling across RAFTI. As discussed previously, the gas and liquid halves of the tank are separated by a diaphragm. A vent valve on the gas line was opened to the ambient environment, and then the vacuum pump was connected to the liquid half. The vacuum pump was then used to fully actuate the diaphragm into the liquid half of the tank. An additional leak check was conducted at this time to verify diaphragm health. Afterwards, the isolation valve from the HTP propellant source tank was opened and the propellant was allowed to fill and prime the intermediate volume between the source tank and the dump tank as well as the RAFTI. The mass of HTP used to prime the system was recorded, the vacuum pump was turned off, and the system isolation valves were closed.

With the spacecraft propulsion primed and the diaphragm in the pre-load configuration, the system was ready for the vacuum fill operation. The vacuum pump on the gas half of the system was turned on first to vacate the ambient environment within the gas lines continuously. At this time, the fill valve was opened, allowing the HTP from the source tank to fuel the flight propulsion tank. The source tank is on a scale and the fill valve remained open until the desired mass of propellant was loaded into the system, accounting for the priming propellant mass. The exhaust line of the gas half vacuum pump was monitored continuously during the fill operation. If liquid was observed in the exhaust, the system would be safed and any propellant loaded into the tank would be removed to prepare for further fault investigation.

Following the successful loading of propellant, the propulsion system was safed. We began by isolating the propellant source by closing the fill valve. For Orbit Fab's propulsion tank, the next step was to deactivate the solenoid valves and power off the GSE connections to the spacecraft. The fill valve was then set to drain, connecting the fill line from the RAFTI interface to the dump tank. The vacuum pump on the liquid line was then activated, and allowed to pump the system down to –26 mmHg. This vacuum was then maintained for a minimum of ten minutes. Once the vacuum pump was turned off and isolated from the rest of the system, a vent valve upstream was opened to allow ambient air to flush the intermediate volume. At this point, the system was in a safe configuration and the remaining couplings were disconnected and capped as needed.

4.2 Lessons Learned

Using the Block 1 RSV to fuel Tanker-001 Tenzing provided valuable insight into the intricacies of ground fueling operations. These insights came in the form of commentary from strategic partners during spacecraft fueling operations, responses to troubleshooting external system anomalies, and dissecting the fueling procedures used by an external party.

Several of the lessons relate to human factors considerations on the GSE during the fueling operations of Tenzing. Proceeding through the complete connection testing and fueling operations showed that Block 1 RAFTI has several opportunities for improvement with regard to operator awareness of the coupling status. Desired improvements include identifying features to positively indicate when the RGC has been correctly aligned and mated to the RSV, and to positively indicate when the fluid connection path is open between the two components.

During the fueling procedure nitrogen and vacuum leak checks were conducted on several continuous volumes of the GSE and spacecraft propulsion system. These leak checks frequently contained large continuous volumes that require a long wait time to notice appreciable leak rates. These large wait times are not possible during the hazardous operation windows for fueling. In an effort to reduce the continuous volumes being leak checked for standard procedure and debugging purposes, a new feature request was established to separate the RSV-RGC installation process from establishing the fluid connection between the GSE and spacecraft.

One of the most critical lessons learned was with regard to the order of operations when making a fuel coupling. On the Block 1 RAFTI, the act of mating the RSV and RGC simultaneously makes the seals against external leak and opens the pintle seals to make a fluid connection. In the sequence of operations used on the Tenzing loading operation, additional feed system controls were present to prevent actual fluid leakage during operations. However, it was noted that the inability to independently create and verify seals to external leak prior to opening internal seals to make the fluid connections imposed constraints on the fueling operation that made the process unnecessarily complex.

This "make-before-break" configuration had previously been captured by internal review and has been incorporated in future RAFTI development. As the coupling and fluid connection are independently controlled with this configuration, an additional indication needs to be incorporated to indicate the status of the fluid coupling separately from the mechanical mate.

5. Initial Flight Data

Orbit Fab manufactured two flight units of the primary tank payload for Tenzing which provided redundancy during spacecraft integration operations and allowed Orbit Fab to validate internal HTP decomposition models through long term exposure testing of the spare propulsion unit. This testing was conducted with the spacecraft loaded to the expected launch ullage and then monitored with pressure readings taken every minute on the legs connected to each end of the primary tank, and on the legs connected directly to the RSV. These pressure readings were logged along with temperature and plotted to track self pressurization rates due to HTP decomposition. The data was used to validate the decomposition model which ensured that the propulsion system on Tenzing wouldn't vent gaseous oxygen molecules from the decomposition of HTP until the spacecraft was on orbit.

Two days after Tenzing's primary tank was filled with HTP, a single burst of pressure readings was taken during spacecraft level software checkouts which confirmed that the pressure in the tank was self pressurizing at the expected rate. After Tenzing launched, tank pressurization data was collected in bursts between passes and the self pressurization rate was compared to that of the flight spare. The data downlinked from the pressure readings is shown in fig. 13 which shows the same 2.2 psi/day self pressurization rate as the flight spare long term system compatibility testing. The propulsion unit on the spacecraft pressurized at a nearly identical rate to that on the ground, further validating Orbit Fab's model of HTP decomposition for future propellant depot development.

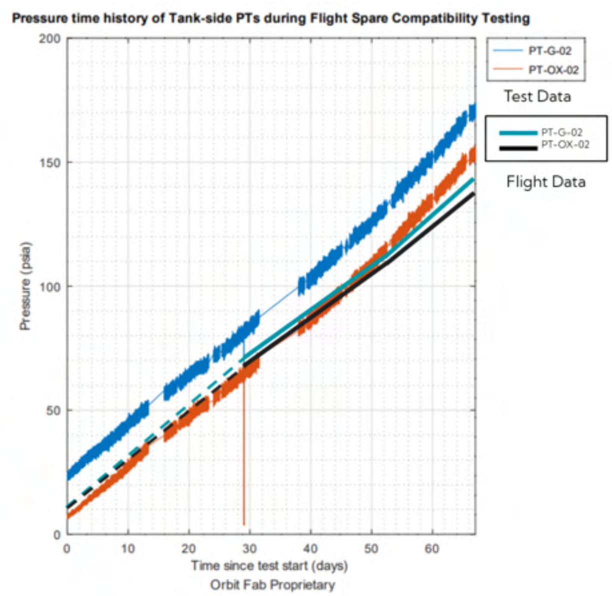

Fig. 13. Flight Spare and Tenzing Self Pressurization

Because of decomposition, it's a common misconception that hydrogen peroxide cannot be stored for long periods of time, but advancements made over the past 50 years and an increased understanding of HTP coupled with its non-toxicity over other toxic storable propellants such as hydrazine, have made it a popular fuel for new propulsion systems.

Generally speaking, the higher the peroxide content, the more stable the High-Test Peroxide is, making it great for propulsive applications at 85% to 98% concentration. This is counter-intuitive, but it's important to note that water within the HTP solution can effectively act as a destabilizing agent, increasing the chances of a peroxide molecule decomposing[8]. There are a number of factors that contribute to the decomposition of HTP. Historically, one of the major contributors has been incompatibilities and impurities of tank and plumbing materials used to store the HTP. This likely the cause of the misconceptions around HTP sourced from old manufacturing processes of the 1940s through 1960s. The surface finish, passivation, coatings, pH levels, and any fabrication flaws of a certain material at different peroxide and stabilizer concentrations and purities within the HTP can affect decomposition and other fuel properties[8].

It's important to note that these compatibility factors affect all potentially storable propellants, but many such as hydrazine benefit from decades of popular modern use and thus have been thoroughly tested for a wealth of different materials and manufacturing processes[8], [9]. As HTP understanding and manufacturing has greatly increased since the 1960s, increasingly popular use of HTP will help determine ideal material and manufacturing combinations for even lower decomposition rates, increasing on-orbit lifetimes at ideal concentrations.

In regards to RAFTI and Tanker-001 Tenzing, these factors have been thoroughly explored and designed to maximize compatibility. As can be seen in the graphs above, the flight spare has a slightly higher overall pressure as it was stored in a higher temperature facility than what the on-orbit Tenzing tank experienced. This helps the case that with proper thermal control and coupling, decomposition rates can be minimized, especially on larger tankers. Additionally, the lower the surface area to volume ratio of the tank, the lower the HTP decomposition rate[8]. As Tanker-001 Tenzing represents Orbit Fab's minimally viable product, and thus the smallest tank we might produce, future iterations of this architecture will have larger tank sizes. Combining both the smaller surface area to volume ratio and better thermal considerations seen in larger tanks, HTP has a great case for long term on-orbit storability with the RAFTI architecture.

6. RAFTI Block 2

The lessons learned from the RAFTI Block 1 testing campaign, ground fueling of Tenzing, and flight have led to the creation of RAFTI Service Valve Block 2. The Block 2 evolution includes improvements to in-space mating and fluid transfer as well as improvements for usability and safety during ground fueling stemming directly from observations made during the Tenzing fueling campaign. This section discusses these improvements, with an emphasis on the latter group.

One of the primary improvements is the modification of the seal arrangement to incorporate the make-before-break operation of the fluid coupling. The approach taken not only makes the fluid path make-before-break, but also completely separates mechanical mate from fluid mate. The Block 2 RSV moves from the face seals used on Block 1 to a series of radial seals, and mounts all seals internal to the RSV body. A probe on the RGC is then driven through these seals, allowing for the fluid operation to be manually performed once the mechanical coupling is verified. This results in a three-phase mating operation, consisting of:

1) Mechanical mate, which clamps the RSV and RGC, and aligns the fluid cores;

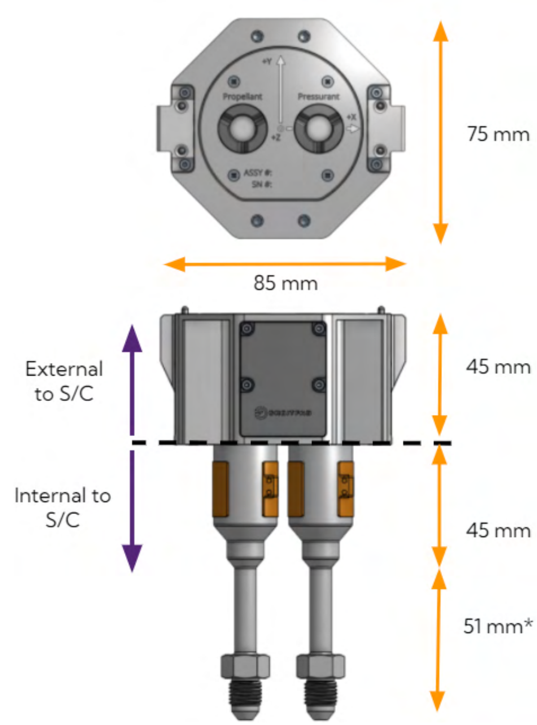

Fig. 14. RAFTI Block 2 Service Valve General Dimensions. Starred dimension may be adjusted for application requirements.

2) Seal against external leak, in which the RGC probe engages seals on the RSV, but has not yet opened the pintle; and
3) Opened fluid connection, where the probe is driven further to open the pintle within the RSV, and allowing fluid flow through the mated interface in either direction.

This is in contrast to the operation of Block 1, where all three of these phases were performed simultaneously by the action of mating the two sides of the interface.

The separation of these phases for creating the fluid connection also enables more clear indications to the operator of the status of the coupling. Due to the change from face seals to radial seals, the mechanical coupling can be designed such that the externally visible interfaces are flush when connected appropriately. This is in contrast to Block 1, where the sealing datums are internal, and the externally visible interfaces are toleranced to guarantee a clearance. While the seal was robust and leak-proof, this resulted in challenges in verifying whether the coupling had been made to tolerance.

The change to radial seals also means that the motion required of the RGC probe between completely decoupled and completely mated with the pintle open is approximately 30 mm. This relatively large motion means that indication of the probe position can be incorporated into the RGC in a large format that is easily visible and interpretable by the operators.

In addition to the make-before-break operation, the shift to

Parameter	Low Pressure RSV
Max Operating Pressure	650 psig
Proof Pressure	975 psig
Burst Pressure	1625 psig
Docking Misalignment	±10 mm (X, Y) ±10° (X, Y, Z)
Mated External Leakage	1×10^{-6} scc/s
Unmated Internal Leakage	1×10^{-6} scc/s
Cycle Life	≥ 1000 cycles
Operating Temp Range	−40 °C to 80 °C
Weight	< 500 g (RSV)
Launch Environmental Loads	NASA GEVs
Expected Compliance	NASA GSFC 8009 AFSPCMAN 91-710

TABLE III
SUMMARY OF THE OVERALL RSV BLOCK 2 SYSTEMS EXPECTED PERFORMANCE

radial seals also enables the RSV pintle to directly include three inhibits against leak. The Block 1 RSV, in contrast, had a single-seal cutoff on the pintle. While this is not a problem in either of the propellant systems on Tenzing—both systems are designed with additional solenoid valves acting as inhibits against propellant loss overboard—the integral inclusion of three seals opens up possibilities for the design of the propellant feed system. In particular, this allows the Block 2 RSV to be installed directly on a dead leg connected to the propellant tank, as is often done with existing fill/drain valves. This increased flexibility simplifies the modifications required to a system to enable on-orbit refueling.

As with the Block 1 hardware, the Block 2 design also incorporates keying to ensure the RSV and RGC can only be mated in the correct orientation. The Block 2 design also includes unique keying for each fluid configuration, allowing for operators to use the RAFTI system for multiple fluids in the same facility or vehicle while preventing incorrect mating of incompatible fluids.

Block 2 also incorporates additional features to improve performance and lifetime on-orbit. The dynamic seals are spring-energized, allowing the use of a wider range of fluids, over a wider range of temperatures, and increased lifetime in the space environment. The seals are also protected from the environment by a set of passively-actuated covers, reducing radiation and atomic oxygen exposure, allowing for on-orbit storage life greater than 15 years in LEO or GEO. The structure of the Block 2 RSV includes the same octagonal face as seen on the Block 1 RSV, which acts as the primary grasp feature for on-orbit operations, but includes additional geometric features designed to improve the ability to grasp the RSV from a range of translational and rotational offsets.

The improvements made in Block 2 allow significantly more flexibility in leak-check and propellant loading operations on the ground. The modified inhibit approach increases the flexibility of the RSV, allowing a wider range of configurations of the fluid system. Together, the modifications make the RAFTI system significantly more user-friendly as a fill/drain valve replacement, all while maintaining the ability to be refueled on orbit.

7. Conclusion

Orbit Fab is developing the technologies and infrastructure necessary to enable widespread on-orbit refueling. The Tanker-001 Tenzing mission is the world' first orbital propellant tanker and a testbed for Orbit Fab's refueling technologies, including the RAFTI Service Valve. RAFTI is a replacement for typical spacecraft fill drain valves incorporating necessary features for grappling alignment and fuel transfer. Tenzing includes two RSV Block 1 units which were first flight qualified then used successfully for ground fueling of the spacecraft with HTP. Several lessons were learned in this process, including the need to have a "make-before-break" fluid path and provide more indication of connection status to fueling operators. These changes have been incorporated into the new RAFTI Service Valve Block 2 design along with improvements to mating, fluid transfer, and radiation tolerance. Block 2 will fly on upcoming Orbit Fab mission including Tanker-002 which will launch to geostationary orbit in late 2022[10].

Acknowledgments

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List of references

[1] J. P. Davis, J. P. Mayberry, and J. P. Penn, "On-orbit servicing: Inspection repair refuel upgrade and assembly of satellites in space," *The Aerospace Corporation, report*, 2019.
[2] J. Schiel, J. Bultitude, A. O'Leary, D. Faber, K. Yang, and G. Kendall-Bell, "A ubiquitous propellant supply chain for enhancement of LEO to GEO transfer services," 2020.
[3] A. O'Leary, Z. Burkhardt, J. Bultitude, D. Faber, and J. Schiel, "Refueling architectures for VLEO missions," June 2021.
[4] J. E. BORETZ, "Orbital refueling techniques," *Journal of Spacecraft and Rockets*, vol. 7, 5 1970.
[5] J. Bultitude, Z. Burkhardt, D. Faber, J. Schiel, and G. Ailts, "On-orbit refueling technology demonstrations aboard the ISS," 2020.
[6] J. Bultitude, Z. Burkhardt, M. Harris, M. Jelderda, S. Suresh, L. Fettes, D. Faber, J. Schiel, J. Cho, D. Levitt, D. Kees, and S. Gallucci, "Development and launch of the world's first orbital propellant tanker," August 2021.
[7] J. Bultitude, D. Faber, J. Schiel, D. Hawes, W. Sigur, P. Putman, and J. Carrico, "A cubesat compliant interface to enable spacecraft docking and fuel transfer," April 2019.
[8] M. Ventura, "Long term storability of hydrogen peroxide." American Institute of Aeronautics and Astronautics, July 2005.
[9] D. Sengupta, S. Mazumder, J. V. Cole, and S. Lowry, "Controlling non-catalytic decomposition of high concentration hydrogen peroxide," 2004.
[10] S. Erwin, "Orbit Fab to launch propellant tanker to fuel satellites in geostationary orbit," September 2021.