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Transit Habitat Government-Reference Conceptual Design Reaction Control System Propulsion Concept Design Data Book

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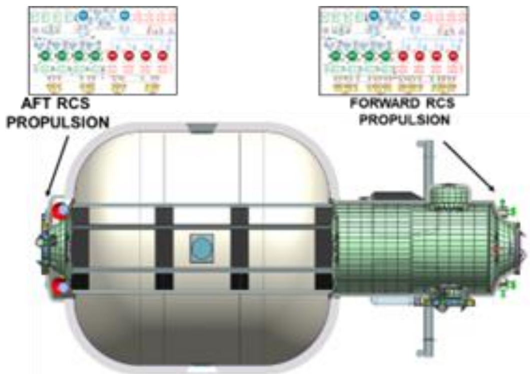

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Executive Summary

The function of Transit Habitat (TH) Reaction Control System (RCS) propulsion is to provide free-flying spacecraft capabilities and to augment Gateway stack control when docked on Gateway. The requirements of multiple propellant replenishments and extensive life operation have significant impacts on selection of the propulsion system concept and components for the RCS.

The intent of this document is to provide insight into the government-reference conceptual design of a propulsion system for TH element. A pressure-fed hypergolic bi-propellant system is the assumed propulsion approach for the RCS. Its architectural concept is being traded within the NASA Moon to Mars architecture.

A pressure-regulated system is examined. The propellants under consideration are Monomethyl Hydrazine (MMH) and Mixed Oxides of Nitrogen with 3% Nitric Oxide (MON3). A peer review was conducted to assess the flow schematic design and propulsion component selection, compliant with a set of assumed requirements. Redundant components to satisfy one-fault tolerance for function and two-fault tolerance against catastrophic events are incorporated in the propulsion concept design. Instrumentation laid out on the schematic would be used to gather data to monitor the health of the propulsion system and to support quantity gauging of the propulsion system fluids. Venting propellant ullage gas overboard during the refilling operations poses a significant concern to the external surfaces of the TH. A liquid/gas separator would be required to eliminate, or at least reduce, the amount of liquid propellant expelled in the vent gas mixture. The technology readiness level of the phase separator for the TH must be advanced. Metal diaphragm and non-positive-expulsion PMD propellant tank systems were traded against each other, with the PMD architecture being selected.

A blowdown concept is also considered for the TH RCS propulsion. Its fluid schematic is derived from the pressure-regulated schematic with removal of assemblies involving the helium pressurization and ullage venting. Its system wet mass is 10% heavier than the pressure-regulated due to thruster performance loss and larger propellant tanks. There is no firm constraint on the propulsion system mass at this phase of the design.

The blowdown concept can offer reduction in component count and operation, that would lead to a more reliable propulsion system. The blowdown concept would also benefit avionics, thermal, power, and structures on the TH. Assessing these benefits will be carried as a future work. Drawbacks of thrust and minimum impulse bit (MIB) variations due to the blowdown operation would be acceptable to Guidance, Navigation, and Control (GNC). Although the blowdown concept has been selected as a current baseline, further evaluation of the concept will be the subject of future work to ensure that the blowdown propulsion operation is appropriate for the HT RCS propulsion.

This document also highlights key trade studies and design decisions, including pros and cons of the selected concept. Other appropriate options for components are pointed out for future assessments. Additional background information and documents for further review are referenced in this report.

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Abbreviations and Acronyms

CG	Center Gravity
CLV	Commercial Launch Vehicle
CONOPS	Concept of Operations
DoD	Department of Defense
DST	Deep Space Transport
EVA	Extravehicular activity
FOD	Foreign Object Debris
FTC	Fluid Transfer Coupler
GNC	Guidance, Navigation and Control
GSFC	NASA Goddard
Isp	Specific Impulse
ISS	International Space Station
LTI	Trans-lunar injection
M2M	Moon to Mars
MGA	Mass Growth Allowance
MEL	Master Equipment List
MEO	Medium Earth Orbit
MIB	Minimum Impulse Bit
MMH	Monomethyl Hydrazine Fuel
MON	Mixed Oxides of Nitrogen
MON3	Mixed Oxides of Nitrogen with 3% Nitric Oxide
MPS	Mars Propulsion System
MSFC	Marshall Space Flight Center
NRHO	Lunar Near-Rectilinear Halo Orbit
NTO	Nitrogen tetroxide
PMD	Propellant Management Device
P_{in}	Thruster inlet Pressure
RCS	Reaction Control System
RTD	Resistance Temperature Detector
TH	Mars Transit Habitat
SCCH	Standard Centimeter Cubic per Hour
SS	Space Shuttle
TLI	Trans-lunar Injection
TRL	Technology Readiness Level
1-FT	One Fault Tolerance
2-FT	Two Fault Tolerance

1 Purpose of Documentation

The Propulsion Systems Team for the TH Element has developed a government-reference-mission propulsion system for the TH Element, which includes provisions for propellant resupply throughout the 15-year mission of this element. The intent of this document is to provide insight into the government-reference conceptual design of a propulsion system for the TH element, which was responsive to the TH requirements and concept of operations at the time. While presenting the propulsion system concept and architecture, this document provides insight into the rationale for selecting this propulsion system architecture, components, and concept of operations. It is hoped that the information contained within this document will be germane and useful to future efforts to develop a hypergol-based propulsion for a TH spacecraft with the capability for multiple propellant resupplies during a multi-year mission.

This document highlights the key trade studies and design decisions, including pros and cons of the options, which leads to the development of the propulsion system. The document also briefly discusses other options for consideration in a future TH RCS propulsion design. Additional background information and documents are referenced in this report for further review.

2 Introduction

NASA's Exploration Systems Development Mission Directorate is developing a strategy for sending humans to the Moon and Mars vicinity, known broadly as the Moon to Mars (M2M) Campaign [(1)]. A government reference conceptual TH design has been developed and refined by the NASA Habitation Systems Development Office. This TH Conceptual Design reflects the latest M2M architecture and establishes a technical basis for a future TH acquisition.

2.1 Concept of Operations of TH

The Concept of Operations (CONOPS) [(2)] presented in Figure 2.1 is notional and subject to change as architectural trades and assessments continue within the M2M campaign. The TH will undergo multiple operational activities throughout its 15-year operational life. The CONOPS, with respective to the TH RCS operations, is briefly discussed in this paper. More details of the TH operations can be found in Ref. 2.

The TH and a boost stage will be launched via separate Commercial Launch Vehicles (CLV) to Medium Earth Orbit (MEO). The TH will be autonomously deployed and functioned independently, prior to docking with the boost stage and initiating the requisite trans-lunar injection (TLI) burn to a lunar Near-Rectilinear Halo Orbit (NRHO) and subsequent Gateway docking. The TH RCS will be used for rendezvous, proximity operations and docking with Gateway. The TH propulsion system may augment Gateway stack control to achieve the required slew rates while attached with Gateway. Prior to assembling into the Deep Space Transport (DST) vehicle, the TH will have undergone shakedown operations. The TH will then be undocked from Gateway and transfer to, and docked with, the Mars Transport System (MPS) using the TH RCS propulsion system.

During the Mars transit, the RCS on the MPS will be utilized for primary vehicle control, with the TH RCS available to assist with orientation control as a contingency. Upon the completion of its first Mars mission, the TH will be autonomously undocked from the DST and returned as a visiting vehicle to Gateway. In many ways, the TH must be designed to operate independently as a free-flying vehicle.

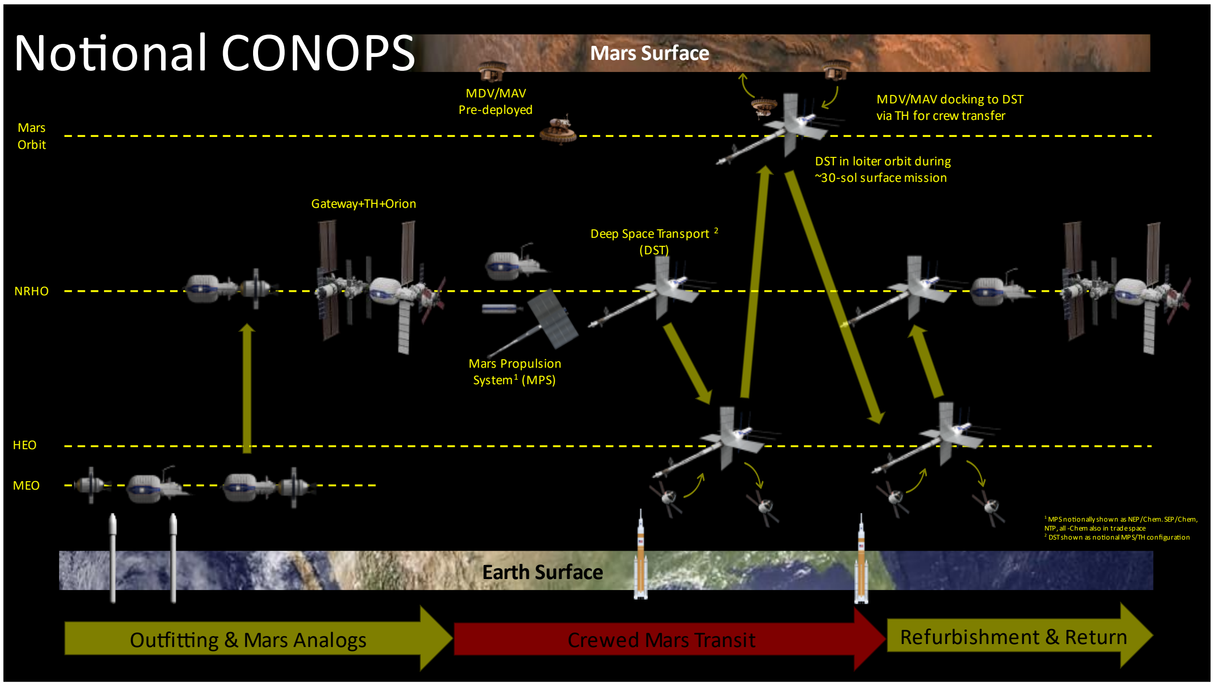


Figure 2.1: Notional CONOPS of Transit Habitat

Notional conceptual design of the TH, shown in Figure 2.2, features two separate propulsion subsystems. A forward RCS will be on the metallic side of the TH and an aft RCS on the inflatable side. Each subsystem has four thruster pods, located on quadrants at the ends of the TH. The forward RCS will have five thrusters per pod, while the aft RCS will have three thrusters per pod. Each propulsion subsystem will have multiple propellant tanks, appropriately mounted on the external surface of the TH.

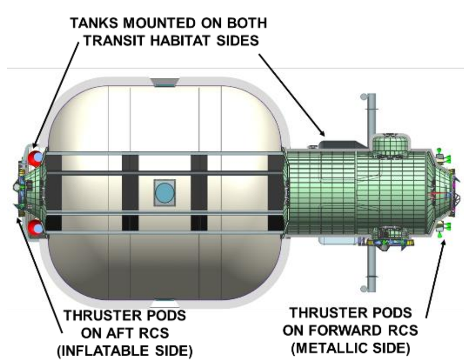


Figure 2.2: Notional TH Forward and Aft RCS Propulsions

A pressure-fed hypergolic bi-propellant system is the assumed propulsion approach for the RCS used by the TH, an architectural concept being traded within the NASA Moon to Mars architecture. The propellants under consideration are MMH and MON3. The pressure-fed propulsion operating with the bi-propellant system has proven hardware heritage for long duration operation. It has been widely used for many spacecrafts.

To be capable of supporting multiple missions and suitable for meeting the TH mass target, it is assumed that the TH RCS will be resupplied propellants multiple times through docking or Gateway interface between mission phases (analogs, MPS shakedown, Mars transit [(3)]). The propellant replenishment capability and reliable long-duration RCS propulsion operation will be key features affecting the propulsion concept and architecture trade selections.

Although the Russian segment propulsion systems (FGB (Zarya), Service Module, and Progress Cargo) on International Space Station (ISS) actively performs propellant resupply in microgravity, the ISS propellant refilling technique and propulsion system components do not appear to be suitable for a deep-space habitation application. A conceptual flow schematic of the TH propulsion system will be presented in a later section of this data book.

2.2 Propellant Load & Refueling Cadence

In 2022, the Advanced Concepts Office at MSFC was commissioned to conduct a multidisciplinary design study of the TH propulsion system. The outcome of the study included trajectory analysis and propellant consumptions for individual propulsion operation events covering a 15-year life span of the Mars mission. Possible refueling events, identified from mission phases, are shown in Table 2.1[(4)].

Table 2.1: Propellant Load Design Point and Refueling Cadence

Event #	TH Burn Event	Delta_V [m/s]	Metallic Side Propellant Burned[(1)] [kg]	Inflatable Side Propellant Burned[(1)] [kg]	Total Prop Burned [kg]	Metallic Side Propellant Total[(1)] [kg]	Inflatable Side Propellant Total[(1)] [kg]
1	Null tip off rates after launch	1	5.81	5.81	11.62	572.88	707.15
2	Maintain attitude in MEO while waiting for boost stage	3	17.43	17.43	34.86		
3	Passive docking with boost stage	5	29	29	58		
17	Active docking with Gateway	45	258.8	258.8	517.6		
21a	Gateway stack control Year 1-3	7.5	261.84		261.84		
21b	Gateway stack control Year 4-6	7.5	261.84		261.84	261.84	
21c	Gateway stack control Year 7-9	7.5	261.84		261.84	657.95	
23	Active undocking with Gateway	45	396.11	396.11	792.22		
24	Active docking with Mars Transit Vehicle	45	390.1	390.1	780.2	706.28	706.28
34	Active undocking with Mars Transit Vehicle	45	316.18	316.18	632.36		
35	Active re-docking with Gateway	45	311.38	311.38	622.76	311.38	311.38
	Usable propellant		2510.33	1724.81	4235.14		
	Propellant residual (3%)		75.3099	51.7443	127.0542		
	Total Propellant Required		2585.6399	1776.5543	4362.1942		
(pink)	Refuel 1: Refuel Metallic Side at Gateway						
(blue)	Refuel 2: Refuel Metallic Side at Gateway						
(yellow)	Refuel 3: Refuel Metallic & Inflatable Sides in Transit from Gateway to Mars Transit Vehicle						
(green)	Refuel 4: Refuel Metallic & Inflatable Sides in Transit from Gateway to Mars Transit Vehicle						

The study concluded that four refueling events (two at Gateway and two during TH transit) would be sufficient. For the metallic side, the system would be refilled after events 21a, 21b, 23, and 34, while the system on the inflatable side would be refilled after events 23 and 34. The maximum propellant amount needed before refueling can be rounded off as 710 kg. The estimate was based on an engine specific impulse (Isp) of 300 sec. The refueling capacity would be 781 kg when adding 10% for reserve. The propellant storage capacity to be sized will include 15%, 10%, and 1% for tank residuals, reserves, and mixture ratio bias errors, respectively. The full propellant capacity will be loaded on ground before launch.

2.3 Assumptions & Requirements of TH RCS Propulsion System

Since the TH is still in its early phases of the design, RCS propulsion requirements have not been formally defined. To develop a propulsion concept, assumptions and tentative requirements are established. They are collectively flowed down from the TH rules and assumption stated in Ref. 3. Some requirements (e.g., safety, fault tolerance) are based on human rated systems.

- Fault tolerance: Propulsion function/operations (e.g., redundant valve - if one valve fails opening, another valve can be used) will be designed for one-fault (1-FT) tolerance. Instrumentation on the propulsion also has redundancy to meet 1-FT for function. The design will have two-fault tolerance (2-FT) for avoiding catastrophic events (e.g., three inhibit barriers to prevent propellant tank over-pressurization and subsequent fluid overboard leakage).
- Safe mode: Propulsion system shall be in a safe mode in an event of a loss of power. For instance, burst disk & pressure relief will be used to prevent propellant tank over-pressurization; appropriate isolation valves are in closed positions without power to ensure three barriers for protecting against overboard leak; valves with back pressure relief will be used to eliminate liquid lockup and over-pressurization of individual feedline segments.
- Life: Operational life will be 15 years. The propulsion system on the TH will be dormant for the Mars mission (up to 1200 days)
  - Components will be compatible with propellants in terms of operation and performance (e.g., permeability, leak, iron-nitrate build-up on NTO system side (unable to operate or valve sticking)).
  - Elimination of fuel and oxidizer mixing within the pressurization system is required under a normal operation.
  - The design will account for leakage through helium control valve (10^{-3} SCCH) to the propellant tanks and external leakage through the ullage venting line, and fluid transfer couplings, particularly the dormancy period of the Mars mission.
- GNC operation limit: GNC can perform its function with any two failed thrusters (e.g., the iso valves on the feedline manifold are arranged to meet this requirement). Eight thrusters will be the maximum of number thrusters simultaneously operated (e.g., helium control valves and feedlines are sized to meet this requirement).
- Propellant Refills: The propulsion system will be capable of being refilled a minimum of four times in space [depending on propulsion architecture concepts, the system can possibly handle more than four refills. This capability will be described in later sections].

Each fluid commodity will be refilled one at a time. It is assumed that TH Element CONOPS will allow the necessary time for this process.

- Remaining propellant in tanks and propellant transfer will be accurately gauged.
- At the end of the final propellant transfer, the supply vehicle will purge the transfer line by flowing helium, to push propellent liquid completely into TH propellant tank. That way, the transfer line system on TH will not need to be vented.
- The supply vehicle will have stand-alone storage tanks of helium and propellants for transferring to the TH (i.e., separate from tanks for the propulsion system of the supply vehicle) to eliminate any contamination of the fluids to be transferred.
- The supply vehicle will have separate helium supply systems (i.e., storage, feed line, compressor (if needed), etc.) to refill pressurant for the TH fuel and oxidizer subsystems. This is due to concerns that if there is only single helium supply storage for both systems, then there can be a potential migration/permeation of propellants from the TH to the supply during the transfer, leading to the unwanted fuel/oxidizer mixing within the TH helium system.
- The supply vehicle will have the capability of relieving TH helium tank pressure in an event of over-pressurization during helium refill.

3 Background on Propulsion Systems with Propellant Refill Capabilities

Extended RCS operational life with multiple propellant replenishments for the TH mission has a significant impact on the selection of suitable a concept and architecture for its propulsion system and components. "Until now, the only space-based vehicles that were designed for refueling from the get-go [initial concept] were the Russian space stations Salyut 6, Salyut 7, Mir, and the Russian segment of the ISS. Added to that list in the last few years are the Peoples Republic of China spacecraft and space station Tiangong and the International Space Station. Because the technology is based on Russian-Soviet experience, the Chinese system is essentially the same as the current Russian (5)". However, these propellant refilling techniques and propulsion components would not be suitable for the U.S. deep-space habitation application. NASA's Gateway, a multi-purpose outpost stationed in lunar orbit, will be equipped with hypergol propellant refill capability. Such technology development under this program would be suitable to the TH application.

The Russian system uses metal bellows tanks with a high residual volume. These tanks are appropriate for a long-life space station with frequent resupply missions but are poorly suited to TH application which requires high expulsion efficiency with only a handful planned resupply missions. When the liquid propellants are refilled in the Russian segment of the ISS, the ullage gas from the metal bellows tanks is compressed back into the pressurant tanks via an on-board compressor system. The compressor system is complex and heavy, and a suitable compressor system has not yet been qualified for U.S. spacecraft. The Russian ullage-compression system has two compressor legs (containing multiple valves, regulators, and sensors on each leg): one for fuel, one for oxidizer. There is a third leg, which serves as a backup and can be used to recompress pressurant on either the fuel or oxidizer subsystems (6). Since the TH has the two separate propulsion systems located at both ends of the TH element, two compressor blocks would be needed. This would lead to a significant amount of additional hardware mass if an ullage-compression subsystem were to be selected. The TH propulsion system would have to carry the ullage-compression system for the entire flight mission to Mars and back to the Gateway. Such an option would not be optimum for the mission.

On the ISS Russian segment, the risk of ejecting liquid propellants, in particular oxidizer, overboard during fluid coupling mate/de-mate cycles threatens optical surfaces, solar arrays, and extravehicular activity (EVA) suits. The ISS manages this risk by locating the Russian propulsive elements at the aft end of the ISS, away from solar arrays, windows, and star trackers, and by defining the aft end as an EVA keep-out zone [(7)]. The TH may not be able to use this approach and will likely need to be equipped with very low-spill automated fluid couplings and have a robust approach for liquid-gas separation during propellant tank venting. The technology level of a fluid transfer coupler (FTC), recently advanced at NASA Goddard Space Flight Center (GSFC), appears promising. The FTC is a command-driven, motorized mechanism that enables easier refueling and replenishment of fluids in space. It was originally designed for Gateway and is now under license for future use by Northrop Grumman [(8)].

One of the most notable US-based technology developments of in-space propellant transfer was undertaken by a DARPA-NASA program called Orbital Express which was launched in 2007. This mission still stands as the most significant known US-developed demonstration of in-space storable propellant transfer [(9)].

4 Propulsion Concepts and Propellant Tanks for TH Options

Options for the propulsion system concepts and propellant tanks that may be suitable for propellant replenishment of the TH are depicted in Figure 4.1. Discussions of the rationale for selecting the propulsion concepts and propellant tanks for the trade study are as follows:

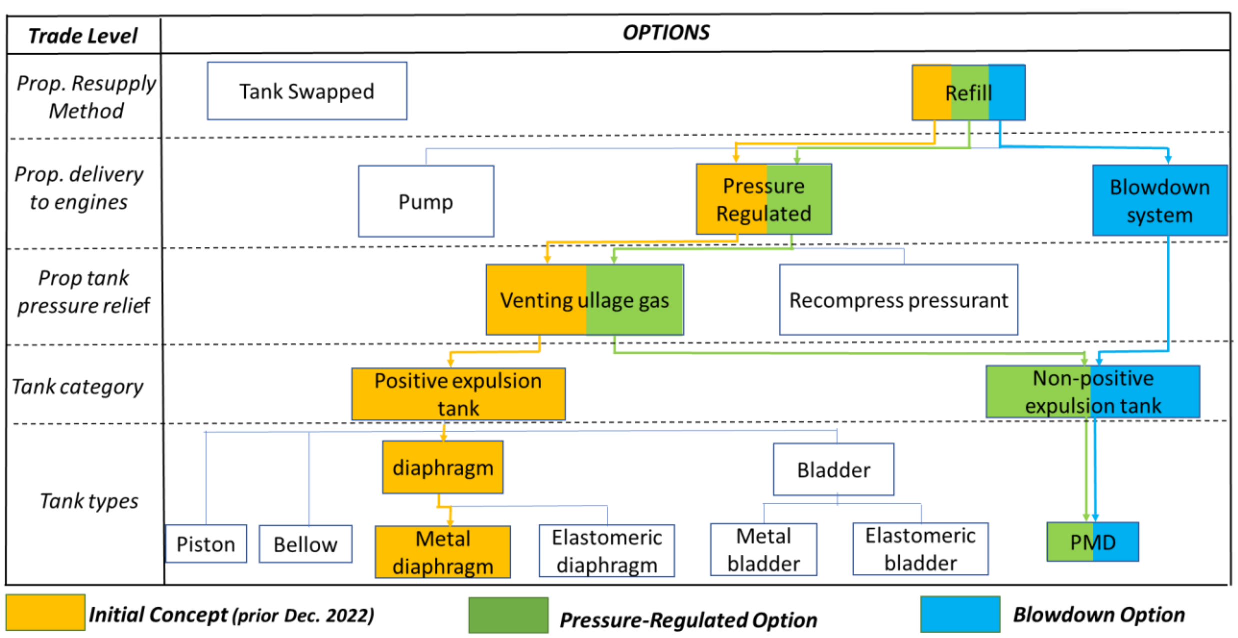


Figure 4.1: Propulsion Concepts & Tank Options for Trade Study

4.1 Propellant Resupply Options

Propellants can be replenished by either swapping tanks or refilling them. Propellant refilling is selected for TH because the propellant tanks, based on the current propulsion system layout, will be dispersed at the forward and aft ends of the TH. For tanks to be swapped, they would likely need to be mounted on pallets in a common location.

4.2 Propellant Delivery Options

There are three methods for delivering propellants to thrusters: pump-fed, pressure-regulated, and blowdown. The options of delivering propellants are shown on the second row of Figure 4.1. A pump-fed system uses pumps to push propellants through the feed lines to the thrusters. The pump system is typically used on vehicles requiring high thrust and high efficiency (i.e., specific impulse) for long, steady-state operations (e.g., Space Shuttle main engines). A pump typically would not be desirable for engines operating in pulsing modes (e.g., RCS). An attribute of a pump-fed system is that the tank pressure is usually relatively low, which could be important for reducing the mass of larger propellant tanks. Another method, called pressure-fed, is to pressurize the propellants using a gaseous pressurant. There are two types of pressure-fed systems: pressure-regulated and blowdown.

- A pressure-regulated system is a type of pressure-fed system. The propellant tank is pressurized with gaseous pressurant (e.g., helium or nitrogen), which is stored in a high-pressure tank (e.g., ~4500 psia) and regulated down to the operating pressure of the propellant tank pressure (e.g., ~250 psia). The liquid propellants are then fed from the tank to the thrusters, maintaining a near constant engine inlet pressure.
- *A* blowdown system is also a pressure-fed system. However, it does not need a high-pressure pressurization system since the pressurant is contained inside the propellant tank for the entire mission. The propellant tank is initially pressurized to the upper end of the engine inlet pressure range (e.g., ~310 psia). As propellants are fed to the thrusters, the tank pressure continually decreases, to a minimally acceptable engine inlet pressure (e.g., 165 psia) for the thrusters. The thruster must be capable of operating over a wide range of engine inlet pressures. GNC must be willing to control and operate the spacecraft with decreasing thrust and impulse bit as the mission progresses. Thrust efficiency, namely Isp, will typically degrade as the inlet pressure decreases, resulting in higher propellant consumption. A blowdown RCS is typically used for missions requiring low thrust and/or low delta V, such as for station keeping.

Based on the propulsion systems described above, the pressure-fed concept, either the pressure-regulated or the blowdown systems, will be well suited for the TH RCS propulsion. A brief qualitative comparison between the pressure regulated and blowdown systems is shown in Table 4.1.

Table 4.1: Key Comparisons between a Blowdown and Pressure-Regulated

Key Comparison	Blowdown System	Pressure-regulated System
Overboard Venting Required?	No. Propellant refilling process would be less complex due to no need of overboard venting and less concerns of propellant contamination and material compatibility of exterior TH and components.	Yes. Anticipation of some propellant loss and pressurant refilling because of tank ullage venting.
System complexity	Less Complexity. Pressurant and propellant within a same tank. No pressurization system required. Operationally simple, less FDIR/software related resources and interfaces	More Complexity. Separate pressurization system is needed to regulate the propellant tanks; however, the system has capability to accommodate leakage/relief operations due to margin on helium.
Propellant Tank size/mass	Larger and heavy. Typically, the ullage volume is at least equal to the liquid propellant volume. Subsequently, the tank size would be large and heavy.	Smaller and light. Initial tank ullage is usually 5-10%. The pressurant enters to tank as needed for maintain a constant operating pressure within the tank
Propellant tank pressure	Decreases as mission progresses (e.g., 350 to 210 psia), propellant is removed from tank and fed to thrusters	Tank pressure is regulated to maintain the optimal value for thruster performance.
Thruster operation and performance (specific impulse)	Degrading Performance (thrust and Isp) as mission progresses. Thruster must be capable of operating at a wide range of inlet pressure (e.g., 350 to 210 psia). Since thruster is designed with an optimal inlet pressure, the engine performance is degraded. Subsequently, more propellant is needed to compensate for the performance loss. It may require large propellant storage capacity or a greater number of propellant refilling.	Thruster is operated with regulated, constant tank pressure, leading to optimum performance all time. Less propellant is needed for mission as compared to a blowdown system

4.3 Propellant Tank Options

Propellant tanks used on spacecraft are typically categorized into two types: positive expulsion and non-positive expulsion. Positive expulsion tanks have a physical barrier between the pressurant and propellants. The barrier can be a piston, bellow, diaphragm, or bladder. The barrier can be made of metallic, polymeric, or elastomeric materials. There are significant concerns with the compatibility of elastomeric and polymeric materials with MON3 on long-duration missions. During extended operations, propellants can migrate through a non-metallic barrier by a diffusion process, that would become problematic to the upstream ‘clean gas’ pressurization system.

In contrast, for a non-positive expulsion tank, gaseous pressurant (i.e., helium typically is used with hypergolic propellants) flows into direct contact with the liquid propellant. A non-positive expulsion tank employs surface tension devices, typically called PMD, within the tank, to assure separation of the liquid propellant from ullage gas as the liquid propellant is expelled from the tank. More details comparing various propellant tank types are described in Table 4.2. The current technology level (TRL) and technology gaps for the utilization of the tanks for the TH RCS propulsion system are also highlighted in the table.

Table 4.2: Propellant Tank Assessment of TH Application

Tank Type	Advantage	Disadvantage	History with in-space refilling	Current Use/Reference for further study	Technology Maturity (as related to TH)	Technology Gap, (as related to TH)
Piston	▪Lowest residual (theoretically) ▪Truly positive expulsion ▪Lends itself to improved gauging accuracy ▪Positive barrier between liquid and gas (advantage for refilling) ▪Propellant location is always known (center gravity knowledge) ▪Eliminates slosh ▪Tank outlet always covered with liquid ▪Minimizes concern for differential drainage and/or fill (if multiple tanks in parallel) ▪Piston actuation can be from multiple sources (gas, electrical, etc.)	▪Tend to be heavy ▪Tend to be small in size ▪Seals are dynamic ▪Possibly of prop to leak/diffuse across piston seal(s) into a clean gas system. ▪Seal life with propellant ▪Requires high dP ▪Potential for seal adhesion	No, but on the ground	▪One known application to be used on launch abort. It has not been used except for the launch abort test flight. Tank size would be smaller than the TH tank. It is for re-flight. Not clear on the life cycle limit. ▪DoD has used piston tanks for missile applications. Propellant storage duration is not known. ▪Piston tanks tend to be small in volume, due to mass. ▪Only serviced on the ground.	TRL ~ 5 to 6 ▪Although not flown in spacecraft, the design is pretty simple. Mass and dynamic seal life are main concerns ▪Scale Up ▪Steelhead Corp. has a piston tank on their web site, but it is in the concept stage.	▪suitable dynamic seals ▪flight compressor (if not venting ullage gas)
Bellows	▪Positive barrier between liquid and gas (advantage for refilling) ▪Propellant location is always known (center gravity knowledge) ▪Eliminates slosh ▪Tank outlet always covered with liquid ▪Minimizes concern for differential drainage and/or fill (if multiple tanks in parallel)	▪Refill with tank residual of ~ 50% ▪May not meet fracture requirements on welded joints. (Fracture/fatigue on flexible metal pressure vessels will always be a risk item.) ▪Probably heavy (but probably not as heavy as a piston tank)	Yes, Tanks on Russian segment of ISS refilled multiple times	Use on Russian propulsion module of ISS	TRL ~5 ▪Although flown by Russians, US has not developed a spacecraft bellows tank. TRL also degraded, due to concerns over flexible pressure vessel integrity/life ▪Scale down from Russian tank	▪Flight compressor (if not venting ullage gas) ▪Retiring/Mitigating fracture concerns with bellows (flexible pressure vessels)
Metal Diaphragm	▪Positive barrier between liquid and gas (advantage for refilling) ▪Propellant location is always known (CG knowledge) ▪Eliminates slosh ▪Potentially low residuals ▪Tank outlet always covered with liquid ▪Minimizes concern for differential drainage and/or fill (if multiple tanks in parallel)	▪Current application is for a single use ▪Require larger delta-P to squeeze out the last portion (~15%) of the residual. ▪Filling process is complicated (maintaining a tight dP across diaphragm).	▪No ▪multi-reversal testing has shown that fracture and leakage occur at 10 reversals.	While hundreds of metal diaphragm tanks have been used and are currently in use in space, none are known to be multi-reversal units.	TRL ~ 4 to 5 ▪Ground test information exists, albeit some not very favorable ▪Single use to date (DoD applications)	▪Flight compressor (if not venting ullage gas) ▪Multiple reversal cycles ▪Assessment of diaphragm compatibility with MON (long duration)

Table 4.2: Propellant Tank Assessment for TH Application (continue)

Tank Type	Advantage	Disadvantage	History with in-space refilling	Current Use/Reference for further study	Technology Maturity (as related to TH)	Technology Gap, (as related to TH)
Elastomeric Diaphragm	▪Commonly used in spacecraft (monoprop hydrazine tanks) ▪Barrier between liquid and gas. However, elastomer/polymer may allow diffusion into clean gas system. ▪Reduces slosh (but not as well as metal-interface tanks) ▪Tank outlet always covered with liquid	Diaphragm elastomer is not compatible with NTO (degrades over time). Would not be suitable for a multiyear mission (for NTO/MON).	No	Dozens if not hundreds of elastomeric diaphragm tanks have been used and are currently used in space applications.	TRL ~4 to 5 (TRL 9 for hydrazine, below 6 for MON)	▪Compatibility with NTO/MON (long duration) ▪Flight compressor (if not venting ullage gas)
Elastomeric Bladder	▪Commonly used in spacecraft (monoprop tanks) ▪Barrier between liquid and gas. However, elastomer/polymer may allow diffusion into clean gas system. ▪Reduces slosh (not as well as a diaphragm) ▪Tank outlet always covered with liquid ▪Minimizes concern for differential drainage and/or fill (if multiple tanks in parallel)	▪Diaphragm elastomer is not compatible with NTO (degrades over time). Would not be suitable for a multiyear mission (for NTO/MON). ▪Probably more residual that in a diaphragm tank	No	Apollo used Teflon bladder tanks, although there were issues with bladder tearing and life limits on expulsion cycles. There would still be propellant permeation issues.	TRL ~ 4 to 5 (TRL 9 for hydrazine, below 6 for MON)	▪Compatibility with NTO/MON ▪Flight compressor (if not venting ullage gas)
Metallic Bladder	▪Positive barrier between liquid and gas (advantage for refilling) ▪Reduces slosh ▪Tank outlet always covered with liquid	▪Require larger delta-P to squeeze out the last portion of the residual. ▪Filling process is complicated / unknown (maintaining a tight dP across bladder). ▪Tech maturation to date is for single-use applications.	No	Technology demonstration (to be confirmed)	TRL ~ 3 to 4 ▪Just Technology at this point. ▪Scale Up	▪Flight compressor (if not venting ullage gas) ▪Multiple reversal cycles ▪Bladder compatibility with MON (long duration)
PMD	▪Extensive history/experience for spacecraft ▪Many configuration options (e.g., vanes, channels, plenum chambers). Some retention devices (i.e., large sponges) might mitigate the need for liquid/gas separator development and also mitigate propellant slosh effects ▪Residuals are well known and understood (from past experience) and are probably less than 1% of prop load.	▪Direct liquid/ullage interface - Absorbs ullage gas over time - Require a liquid/gas separator to vent ullage from tank for refilling. - Liquid location varies (due to vehicle accelerations) ▪Configuration can be a very complicated design (depending on mission requirements). ▪It can be heavy (depending on mission requirements and potential for severely adverse acceleration fields at beginning of burn). ▪Slosh	Demonstration of hydrazine propellant refilled on Orbital Express mission	Widely used for single mission. Not much, if any, experience with in-space refueling.	TRL ~ 6 (Could be higher, depending on mission requirements.)	▪Liquid/gas separator ▪Minimizing impact on clean gas (pressurant) system/components ▪Flight compressor (if not venting ullage gas), compatible with prop vapor

The type of propellant tanks to be used on the TH propulsion will have significant impacts on CONOPS for refilling propellants and propulsion operations. Propellant tank option paths, as previously shown in Figure 4.1, point to two choices: positive expulsion and nonpositive expulsion. As previously mentioned, the initial TH RCS concept has been baselined with metal diaphragm propellant tanks. The impermeable-barrier, positive-expulsion propellant tanks would allow for the overboard venting of only the ullage pressurant for releasing the tank pressure during refilling. Because of the impermeable barrier in the propellant tank, there is virtually no concern for ullage gas being entrained into the downstream feedline system. However, the tanks with a metal diaphragm or bladder are typically a single-use component, due to the permanent deformation of the metallic membranes as propellant is expelled from the propellant tank (i.e., plastic yielding and strain hardening during the reversal process). The predictability of the pressure required to move the membranes after refill cycles is a concern. Perhaps, investments to test and advance the technology readiness of new metallic materials (e.g., nitinol alloy [(10)]) for tank diaphragms could make metal diaphragm tanks more viable for the TH application, and the US spacecraft industry in general.

Surface-tension PMD tanks have been tentatively selected for the TH. A liquid/gas separator will be required to eliminate, or at least greatly reduce, the release of liquid propellants overboard due to venting during refilling of the propellant tanks. Ullage gas, which is a mixture of pressurant and propellant vapor, would potentially cause contamination/ material concerns due to compatibility of the external surface of the elements (i.e., TH, Gateway) with the liquid or vaporous propellant. The inflatable portion of the TH is primarily a layer of Beta Cloth to protect the inner layers from abrasion and atomic oxygen. This layer has not yet been tested for material compatibility with hypergolic propellants. To reduce the contamination concern, the vent outlet can be placed, and/or pointed, away from the TH external surface.

On the other hand, a pressure-fed system employing blowdown mode does not need to release the ullage gas for refilling. However, the blowdown architecture has the weaknesses documented in Table 4.1. Further review of the initial concept has led to a trade study between the two other options shown in Figure 4.1: the pressure-regulated (in green) and blowdown (in blue) concepts, but with both using PMD propellant tanks. This report will detail these two concepts at length. A trade study between them will lead to down selection of TH RCS propulsion concept. Descriptions of both systems will be presented in the following sections.

5 Pressure-regulated Propulsion concept

For a pressure-regulated system, ullage gas must be removed from the propellant tanks to replenish the liquid propellants. The ullage gas removal can be either vented overboard or recompressed into the high-pressure pressurant tanks via a compressor system. As described in Section 3, the option of recompressing pressurant is not desirable for the TH due to the system complexity and mass penalty. Consequentially, venting the ullage gas overboard has been considered for the TH mission. Releasing the ullage gas overboard, however, has some downsides. The resupply vehicle would have the burden of delivering the high-pressure pressurant gas to re-pressurize the TH pressurant tanks back to flight pressure. At least two pressurant resupply couplings (i.e., for redundancy) would be required at the interface between the TH and the resupply vehicle. These high-pressure (i.e., ~4500 psia) interface couplings are leakage points that are susceptible to damage during mates/de-mates and orbital debris/micrometeoroids impacts. Damage to the couplings could make the couplings unusable and/or could result in overboard leakage of the TH pressurant. An added valve could mitigate the overboard leakage risk.

On the other hand, if a compressor option is integrated into the system, many components, and a considerable amount of mass, as described in the previous sections, are added to the propulsion system. It would not be a desirable choice to carry the volume and mass of compressor system on the TH for an entire Mars mission. Another possibility is that the compressor system is a part of the supply vehicle, which would lead to additional trades with inclusion of the supply vehicle. These trades are beyond the scope of the current study.

5.1 Flow Schematic of Forward RCS Propulsion Concept

A flow schematic of a pressure-regulated propulsion system for the TH has been conceptually formulated. Figure 5.1 shows the forward RCS, composed of helium pressurization systems, propellant tanks with feed lines, fluid refill assemblies, and thruster pods. The schematic includes redundant components for one-fault tolerance for function and inhibit barriers for two-fault tolerance against catastrophic events, such as substantial overboard leakage of propellants or pressurant and over-pressurization of the propellant tanks. The valves on the spacecraft propulsion system have been arranged to meet requirements of redundancy for function and inhibit barriers to preclude gross liquid leakage. Appendix A further discusses the basic component arrangement features in the flow schematic. The current schematic has been developed for normal propulsion operations. Considerations of off-nominal operating conditions may lead to some changes in the flow circuits and components. Revisions for off-nominal conditions and operations will be addressed in future work.

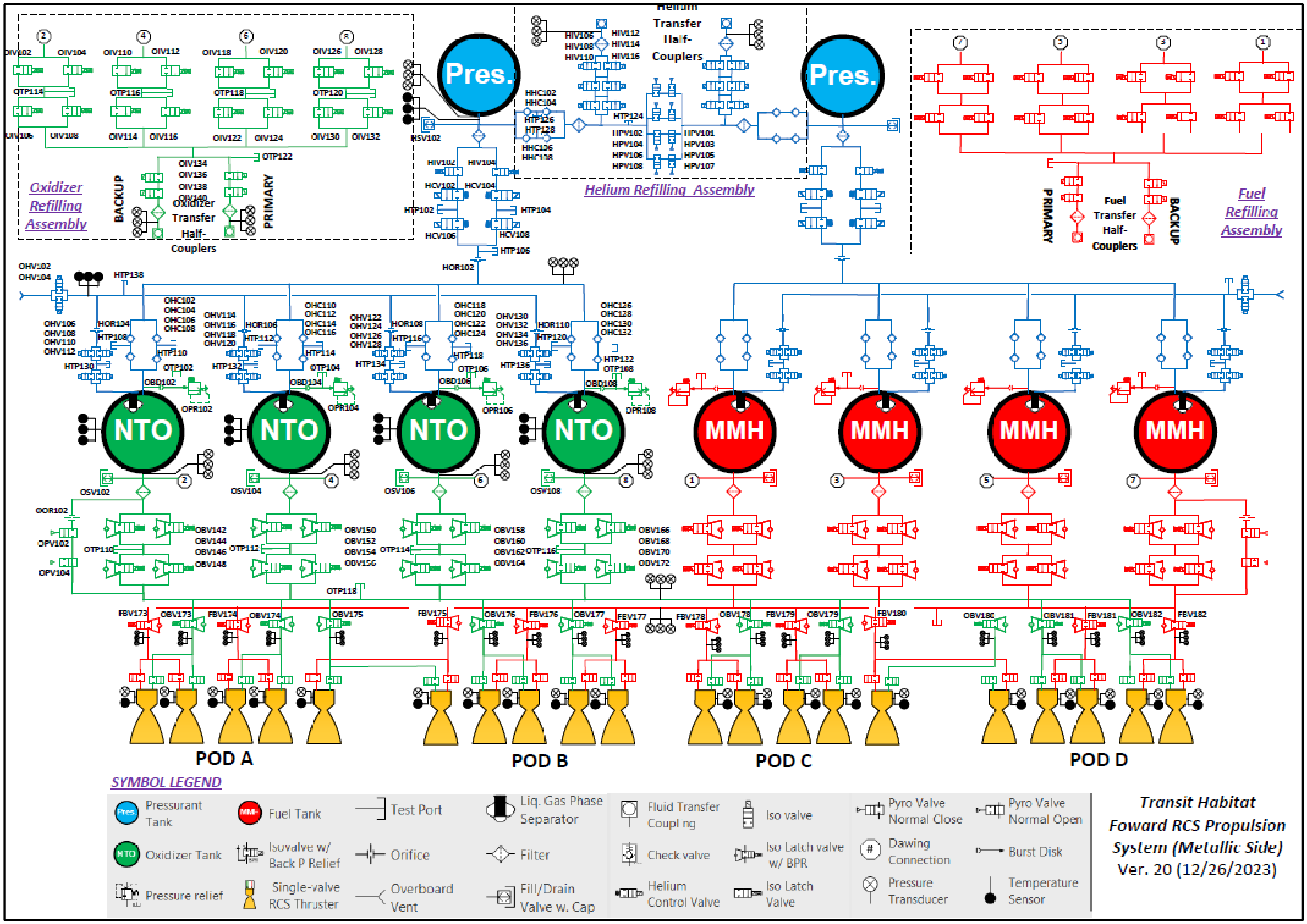


Figure 5.1: Pressure-Regulated Propulsion Flow Schematic of Forward TH RCS

5.2 Flow Schematic of Aft RCS Propulsion

The aft RCS propulsion concept has a similar flow schematic as the forward RCS, except for the thruster pods. Each aft RCS Pod has three thrusters, as opposed to five thrusters in the forward RCS Pod. The difference in the number of thrusters per pod between the aft and forward RCS propulsion systems is due to specific design requirements aimed at optimizing the overall control operational efficiency of the system. The objective of the RCS placement assessment was to identify ideal locations and directions vectors from thrusters that could provide 6 DOF control while meeting key performance and safety criteria. The flow schematic of the aft RCS is shown in Figure 5.2. Since the TH concept design is still in its early phase, detailed RCS operation has not been well defined. To minimize the differences in component sizes between the forward and aft propulsion systems, the components in the aft system are conservatively selected to be the same as the ones in the forward RCS.

It should be noted that the propellant load and refueling cadence described in Section 2.2 was based on the same tank sizes in both forward and aft systems. Hence, a primary difference between master equipment lists of both systems is in the thruster pods. The lists will be presented in a later section.

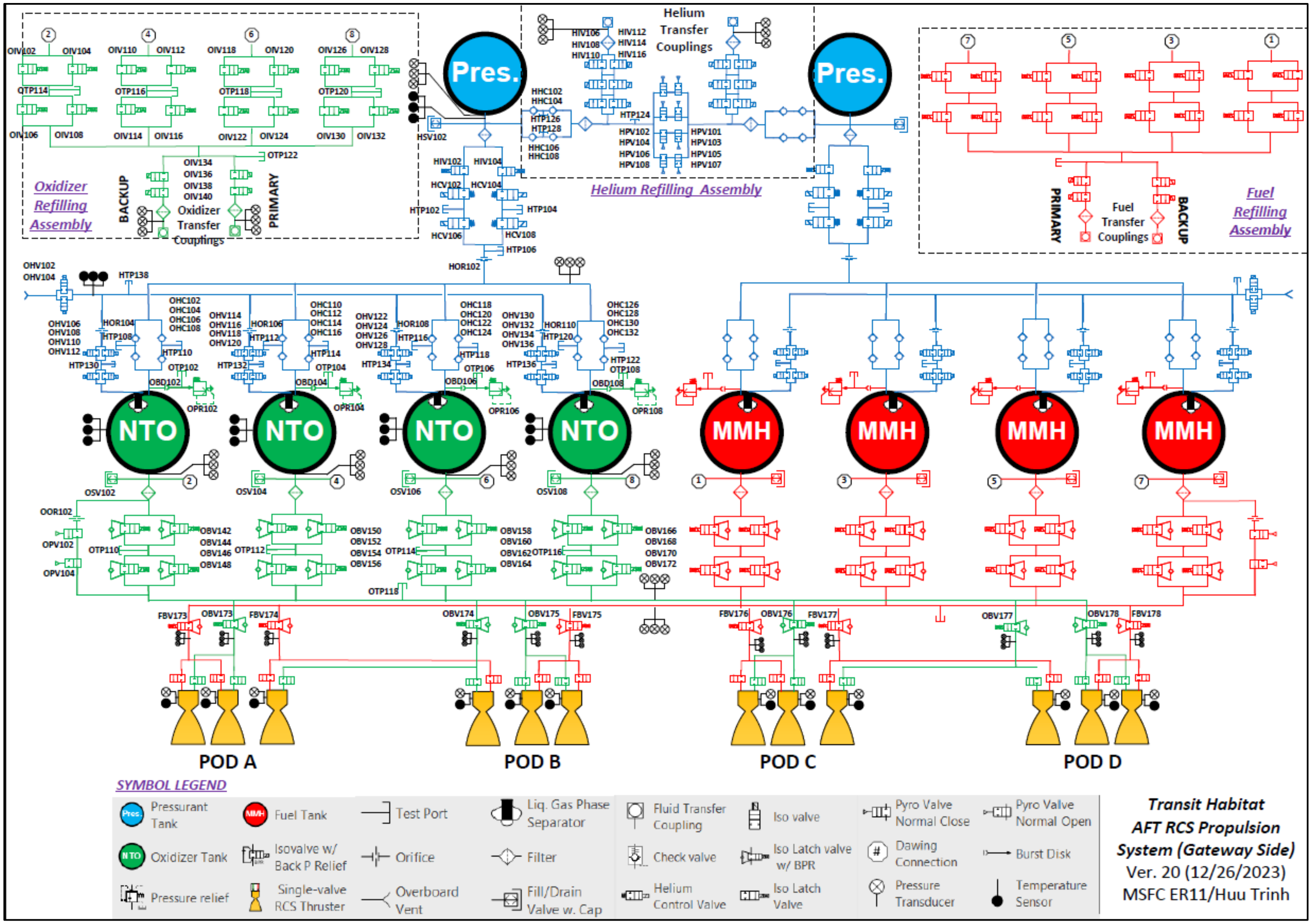


Figure 5.2: Pressure-Regulated Propulsion Flow Schematic of Aft TH RCS

A peer review was conducted of the flow schematic and components, to assess compliance with requirements, assumptions, and ground rules [11]. The review team considered component compatibilities with long-duration propellant exposure (e.g., permeability, iron-nitrate build-up on NTO system side), internal leakage from the high-pressure helium source to the propellant tanks, and external leak through the ullage venting line, and fluid transfer subsystem, particularly during the periods of dormancy (e.g., transit to Mars). Several technical issues and technology gaps were identified during the peer review. Sub-assemblies of the pressure-regulated system will be described in the following sub-sections.

5.3 Pressurization System Assembly

As shown in Figure 5.1, the fuel and oxidizer legs have their own helium pressurization subsystems to reduce the risk of propellant mixing within the pressurization subsystem. The helium pressurant is regulated with control valves, informally called "bang-bang" regulation. Figure 5.3 shows the schematic of the system for the oxidizer side. The component arrangements for the fuel and oxidizer sides are identical. The helium control valves (HCVs) have been selected to provide additional barriers to mitigate the catastrophic over-pressurization of a propellant tank. If regulators were in place of the control valve, the regulators could not be expected to prevent helium leaking internally into the propellant tanks over time. The regulator leakage is a great concern for an extended mission. To provide another layer of protection against an over-pressurization event, a burst disk/ pressure relief valve assembly will be installed just upstream of each propellant tank. This additional protection would be consistent with a human-rated system.

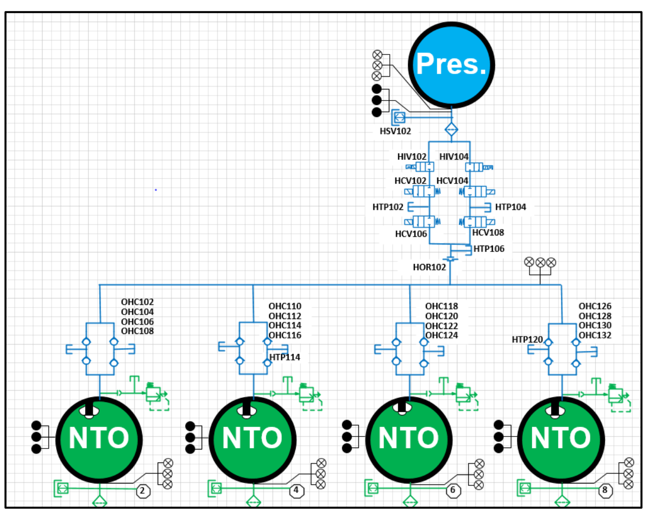


Figure 5.3: Pressurization System Assembly of Oxidizer Side

Keys features of component functions and operations on pressurization assembly.

- There are two parallel legs of helium control line circuits for redundancy. Each has an isolation latch valve (HIV102, HIV104) respectively.

  - The latch valves will be open during operating series of pulse mode profiles. They will be closed during extended non-operations (dormant period, etc.) to keep helium control valves (HCV) and downstream valves from exposing high pressure conditions.
  - The latch valve would provide one barrier to protect against propellant tank over-pressurization.
- Helium control valves (HCV-102/HCV106 and HCV-104/CHV108) are in series on each leg.
  - The valves in series would meet one-fault tolerance (1-FT) for function in the event of the valve failed open/ failed closed.
  - The valves would provide two barriers to protect against propellant tank over-pressurization.
  - *Notes:*
    - Pressure regulator is not selected due to soft-good material compatibility issue and long operation life. The regulator cannot be counted as a barrier against internal leakage.
- Orifice HOR 102 is used to control helium flow (i.e., to reduce the pressure surge) to the propellant tank.
- Parallel series check valves (OHC102/OHC106 and OHC104/OHC108, etc.) are used:
  - to meet 1-FT on function if one check valve leg is blocked or one check valve fails open.
  - to keep liquid propellant from flowing upward into the helium pressurization system.
  - to prevent flow from one tank to another while venting tank ullage.
- The pressurization assembly has three barriers (i.e., two with helium control valves + one with isolation valves) to protect against a catastrophic event of propellant tank over-pressurization.
- The system will be designed to account for helium leak through the valves for an entire of the dormant period. Estimating helium leaking quantity over the period will be a forward work. In event of the propellant tank over-pressurization, the pressure can be released through the tank ullage gas venting assembly . Furthermore, an option for adding a pyro valve downstream of the orifice for extra protection for launch should also be evaluated in the future.

5.4 Propellant tank and Feedline Manifold

Assembly of the propellant tanks and feedline manifold is shown in Figure 5.4. Selection of four tanks per propellant commodity is based on tank size and their installation locations within the TH structure. The tanks are mounted appropriately on the external circumference of the habitat. Isolation valves with a back pressure relief feature are installed downstream of the tanks. Propellant from the tanks flows into a common propellant manifold, which feeds propellant to the thruster pods. Propellant (fed to the thrusters or refilled from a supply vehicle) can be controlled independently for individual tanks with this arrangement. There is a possibility of connecting the tanks in a series, which could reduce the component count. The serial connection would be simpler and more reliable for the long mission application (i.e., 15 years is a very long time to be dependent on a lot of valves needing to operate). Further assessment of the tanks connected in series will be addressed in future work.

The feed line assembly for each propellant commodity also has a priming line to provide a bleed flow at the time of system activation. The intent of the initial priming line is to reduce the magnitude of the surge pressure (i.e., waterhammer) within the feed system at the initial filling of the feedline filling.

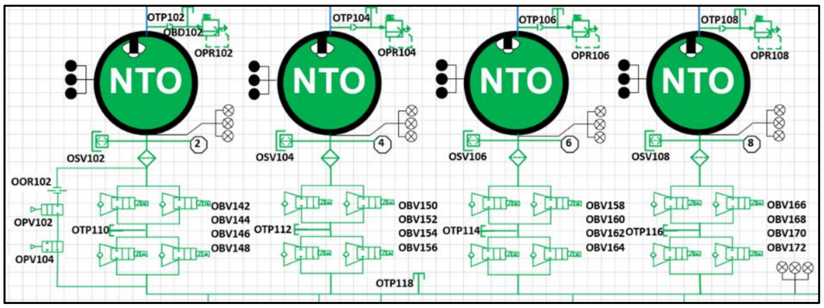


Figure 5.4: Propellant Tanks and Feedline Manifold

Key features of component functions and operations on propellant tanks & feedlines

- Propellant tanks are connected in parallel. They have the following features:
  - Tanks are protected from an over-pressurization event with pressure relief (OPR102, etc.), which is located at the tank inlet of the pressurant. Burst disk (OBD102, etc.) is upstream of pressure relief to avoid risk of iron nitrate accumulation within the pressure relief valve.
  - Tanks are equipped with a PMD to ensure that gas-free liquid propellant is delivered to the thrusters. PMD design will be based on the PMD within the National Space Transportation System (NSTS) Orbiter RCS tanks [12] to accommodate a nearly omni-thrust-vector direction with an acceleration field ranging from 0 g to 0.07 g. This acceleration range is reasonable for the TH mission.
  - Tank ullage gas will be vented through liquid-gas phase separator during the propellant refilling.
  - Fill/drain service valve will have 3-barriers feature with cap for ground service.
  - Propellant will be refilled at the tank outlet, near location of the fill/drain service valve.
- The feedline will be equipped with a priming line per propellant commodity.
  - The purpose of the priming line is to reduce pressure surge at the initial feedline priming.
  - Two pyro valves, initially OPV102 closed and OPV104 open, are in series.
  - OPV102 is open when priming the feed line. OVP104 is closed when the priming is completed. This priming operation is required only one time, during the initial activation of the TH propulsion system. Since the pyro

valve and the priming line are small, there would be only a minimal concern of the pyro valve closing action leading to a pressure wave which could cause the adiabatic-compression detonation (ACD) of the MMH downstream of the pyro valve.
  - Pyro valve is very reliable. No redundancy is required.
- Isolation valve set (OBV142, 144, 146, and 148, etc.) have back pressure relief.
  - The valve arrangement would allow each tank to be operated [fill, drain, refilling, etc.] individually.
  - the iso valve set would meet the 1-FT for function of isolating individual tanks for operation (if needed) and propellant refill. Subsequentially, they provide two additional barriers to protect the propellant overboard leak through the thrusters.
  - Back pressure relief feature is to preclude the liquid lockup and over-pressurization due to thermal expansion of the liquid. Back relief pressure is normally set ~150 psia above the upstream pressure. Arranging valves with back pressure relief in series would stack up the final downstream pressure much higher than we intend to have the pressure released to the upstream. Per suggestions from the peer review team, the back relief pressure of a lower value (~50 psi) is selected as a baseline.
- A common feedline manifold will be designed to connect all tanks to thruster manifolds.

5.5 Thruster Manifold Assembly

For the forward RCS system, four thruster pods are located on the forward end of the TH metallic side, at 90-degree intervals around the circumference. Each pod has five thrusters. The pods share the same propellant feed line manifolds. The thruster manifold assembly is shown on Figure 5.5.

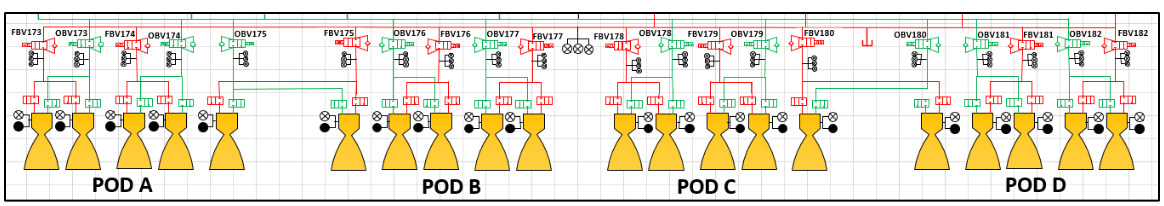


Figure 5.5: Thruster Pods and Manifold Assembly

Within each pod, thruster manifolds distribute the propellants to each thruster pair. If an isolation valve on a thruster manifold fails closed or a thruster valve leaks (and the isolation valve would be closed), two thrusters associated with the isolation valve would be removed from operation. In this event, the design still satisfies one-fault tolerance for function since it is assumed that GNC can perform its function with two thrusters out. The propellant and helium lines will be sized with a capability of operating eight thrusters simultaneously**.**

Key component functions and operations within the thruster manifold assembly

- Isolation valves have back pressure relief (OBV173, FBV173, etc.)
  - The iso valves will protect against thruster valve leak.
  - Back pressure relief would eliminate liquid lockup on feedline which could lead to over-pressurization of individual line segments.
  - Closing one isolation valve on the feedline manifold results in two thrusters out.
  - The valve arrangement would meet the 1-FT on function.
- Five thrusters per pod
  - One thruster of a pod (e.g., Pod A) will share an isolation valve (e.g., OBV175 and FBV175) with one thruster on another pod (e.g., Pod B).
- *Notes:*
  - There would be four barriers against the propellant leaking through a thruster (i.e., two propellant tank iso valves + one manifold feedline iso valve + one thruster valves)
  - There is an option to use a dual valve on each thruster to meet the dual fault tolerance requirement to preclude gross propellant leakage without a need for an isolation valve on the thruster manifolds. The redundant thruster valve would be equivalent to have another thruster manifold iso valve for an individual thruster. However, this option would double the number of valves. Assessment on thruster valve reliability will be performed in future.

5.6 Propellant Refilling Assembly

The oxidizer refilling assembly is shown in Figure 5.6. The assemblies for both propellant commodities are shown on the propulsion flow schematic in Figure 5.1. An array, composed of four isolation valves, are arranged in a parallel-series configuration. The downstream side of the isolation valve array, respective to the propellant refilling flow direction, is connected to the outlet of an oxidizer tank. The upstream side of the isolation valves arrays are linked to a common line manifold. During the refilling process, the propellant is fed to the manifold through fluid transfer couplers (FTCs). This valve arrangement would allow each tank to be serviced individually. The peer review team suggested an option to use a pyrotechnic valve ladder, instead of the isolation valve arrays. This option would require sixteen pyro valve legs (i.e., four tanks and four legs per tank) since there will be four propellant refills for an entire mission.

Each propellant refilling assembly has two fluid transfer half-couplers, which mate to another half-coupler on the supply vehicle. It is assumed that the active half of the coupler will be on the supply vehicle, while the passive half on the TH. One set of FTC

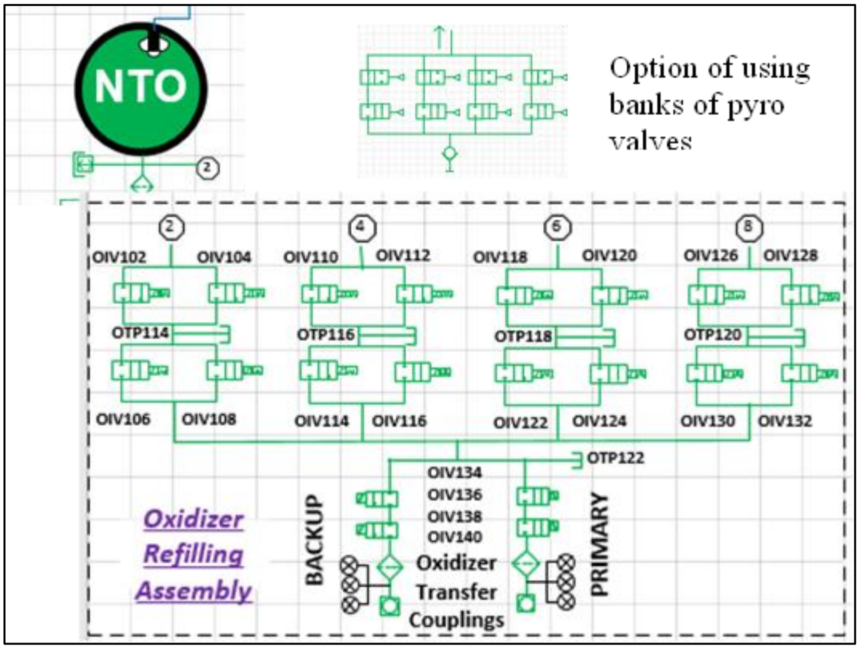


Figure 5.6: Propellant Refilling Assembly of Oxidizer Side

serves as a primary, and the other is a backup. The supply vehicle must have fluid couplers which are compatible with the TH fluid couplers. The current design is assumed that the supply vehicle will flow helium to purge liquid propellent on the propellant refilling lines to TH tank at the end of refilling. Therefore, a separate purge system on TH side would not be required. Further assessment on this assumption will be on future work.

Key features of component functions and operations of the thruster manifold assembly

- Set of isolation valves (e.g., OBV 102, 104, 106, 108) are arranged in series and redundant as a figure-eight configuration. The set is then connected to propellant tanks.
  - The valve arrangement would meet the 1-FT on function regarding either valve failed-closed or valve failed-open.
  - They will provide two barriers to protect against gross overboard liquid propellant leakage.
  - They will provide capability of refilling individual tank
  - The valves do not need back pressure relief capability for protecting against liquid lockup since the propellant on transfer line is purged at the end of refilling.
- A common-manifold iso valve pair in series (OBV 134 and OBV 136) provides two additional barriers, to meet fault-tolerance. Protecting against an overboard leak (three barriers are required).
  - The two valves in series would be able to prevent against valve failed-open on the primary transfer coupling leg.

- All valves will be installed in a reversed orientation (like the ones on the helium refilling assembly) with a custom filter at valve outlet, to prevent against overboard leak.
  - Due to the iso valve being installed in a reverse-flow orientation, the valve con-ops will follow steps of opening the iso valve on TH side first, then valves on the supply vehicle. For closing, the iso valves on TH side will be closed first, then the ones on the supply vehicle will be closed later.

5.7 Helium Refilling Assembly

The helium refilling assembly is shown in Figure 5.7. In contrast to the primary and backup fluid transfer couplings, as seen on the propellant refill assemblies, the helium subsystem refilling requires the use of both half-couplers to transfer helium separately to fuel and oxidizer sides.

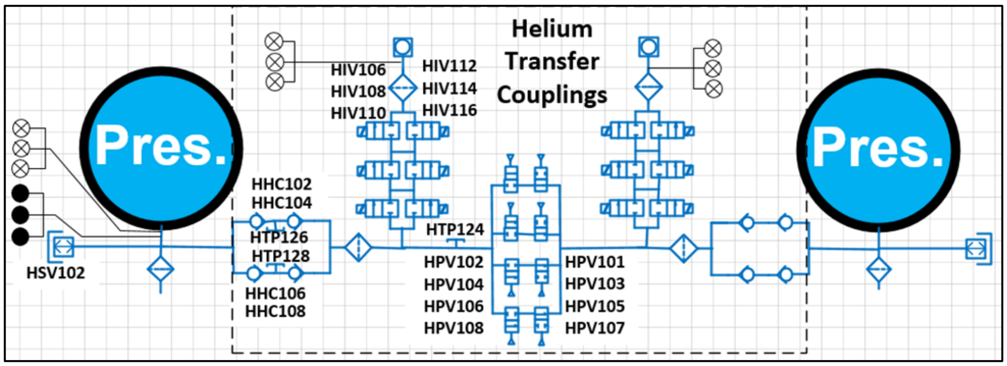


Figure 5.7: Helium Refilling Assembly on Oxidizer Side

If one helium coupler fails (one-fault tolerance for function), helium will be transferred through the remaining coupler to the fuel and oxidizer pressurization subsystems. This would require a pyrotechnic valves leg, connecting both subsystems on the oxidizer and fuel sides, to be activated. There are four legs in the pyro valve ladder. Each valve set within the pyro valve ladder would be used for each discrete helium transfer. Hence, the arrangement will allow the helium cross-transfer up to four times. The number of times is consistent with the requirement of four refills. Additional number of refills can be done if there is one set of the unused pyro valves left.

There is a concern of undesired mixing of fuel and oxidizer vapors within the helium pressurization subsystems once the pyro valve has been activated. Check valves installed in the low-pressure helium subsystem would mitigate (i.e., eliminate or greatly reduce) the mixing of helium between fuel and oxidizer subsystems during the helium transfer. However, the check valves could also cause valve chattering issues. Further assessment of the check valves arrangement will be conducted in future. The remaining pyrotechnic valve on the activated leg of the pyro ladder will be closed upon completion of the helium transfer.

Key features of component functions and operations in helium refilling assembly

- Three sets of isolation valves between the helium tank and the transfer coupler are arranged in a figure-eight configuration.
    - The valve arrangement would meet the 1-FT for function in an event of the valve failed open/ failed closed.
    - They provides 3 barriers against overboard leakage. It is assumed that the FTC disconnector can't be counted as a barrier.
- Nominal helium refilling requires using both transfer couplers for transferring helium to fuel and oxidizer sides separately.
    - This refilling requirement would be different from propellant refilling. Note that propellant only needs one FTC. An extra coupler is for backup.
    - If one helium coupler fails, helium can be transferred through the remaining coupler for both pressurization systems of the fuel and oxidizer sides. This would require one pyro valve leg to be activated per each refill.
        - There are four sets of the pyro valves. Hence, the valves system can be used for refill more than 4 times (if needed).
        - Risk of fuel/oxidizer mixing on the helium pressurization system is recognized once the pyro valve is activated. Check valves would reduce the chance of helium on one pressurization side flowing into the other during the helium transfer. There is a concern of check valves not performing as expected over long periods of time. The assessment of this concern will be addressed in future work.
- Pyro valves on the helium cross-transfer provide a physical barrier between the two helium systems on the fuel side and the oxidizer.

<u>Note</u>:

- Built-in filters at the outlet of the pyro valve ladder are to catch FOD from the activation of pyro valve. As such, there is no need for an individual filter between any two pyro valves within a same set.
- Isolation latch valve arrangement on the transfer coupling addresses a concern for FTC leakage (1-FT). For this event, the other FTC will be used for the helium transfer.
- The isolation latch valves would be installed in a reverse orientation, to protect against an external leak when not mating with the supply vehicle. Each latch valve has its own filter. Hence, it would need a custom filter at the valve outlet. A concern is that the iso latch valve has no history of being used in this configuration.
- The Con Ops plan is to use the iso latch valve as follows: a) open the iso valve first; b) open the valve of supply vehicle for helium transfer; c) close the valve of the supply vehicle; d) close the iso valves on TH. It is noted that such Con Ops would leave helium trapped on the FTC at high pressure. It is possible that the trapped helium must be vented for the FTC de-mating. Further assessment of this circumstance will be conducted.
- An option is to use a bank of pyro valves, instead of the iso latch valves.

5.8 Tank Ullage Gas Venting Assembly

As previously described in the propellant refilling process, ullage gas will be released overboard through a venting line assembly. The ullage gas venting assembly on the oxidizer system is shown in Figure 5.8.

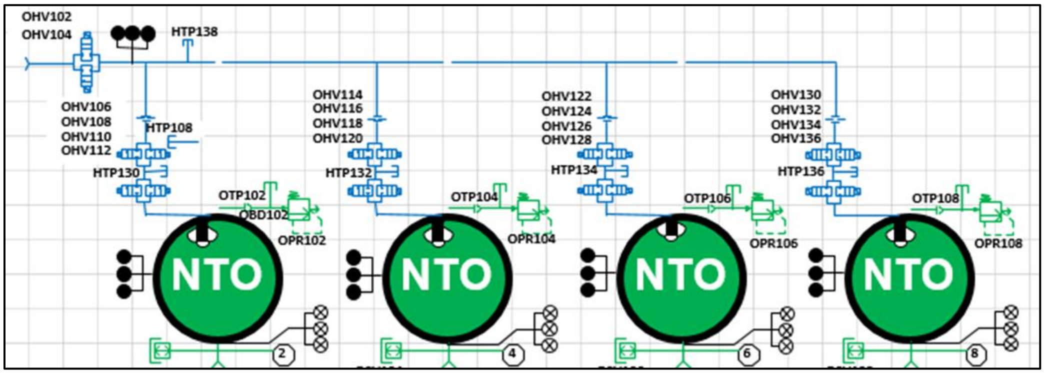


Figure 5.8: Oxidizer Tank Ullage Gas Venting Assembly

The venting line system connects liquid/gas separator devices, which are located within the tanks. The function of the separator is to preferentially allow ullage gas, consisting of helium and propellant vapor, to be released, while keeping the liquid propellant within the tanks. The vent outlets will be placed and pointed away from the TH to reduce chances of the propellant contamination of the TH external equipment and surfaces. The outlets will be designed with consideration of minimizing or eliminating propulsive effects of the venting.

Key features of component functions and operations on helium refilling assembly

- Liquid/gas phase separator only allows ullage gas (i.e., helium and propellant vapor) to be vented.
  - Its function is to release ullage gas for reducing tank pressure prior propellant refilling.
  - Multiple venting operations would be performed during each distinct liquid propellant resupply operation.
  - Individual tank (one tank at the time) would be vented separately.
- Sets of isolation valves are arranged with a figure-eight configuration.
  - The arrangement would meet 1-FT for function to protect against valve failed-closed or failed-open.
  - It also provides two barriers to protect overboard leak.
- Adding an orifice on each venting propellant tank leg would reduce pressure on the venting line manifold to prevent backward flow to another propellant tank. The tank isolation valves on the venting line only protect against forward leaks (i.e., leaking from the tank to the venting manifold). If pressure downstream the valves become too high, this condition would lead to backward flow during venting other tanks. Hence, the orifice is used to mitigate this issue.

- Valve set (OHV102 and OHV104) is added to provide a third inhibit barrier against an external leak.
- The overboard vent must be placed away from TH, to reduce a chance of TH external equipment and surface contamination by the propellants. The vent must be designed of not reducing acceleration on the TH.

5.9 Propulsion System Instrumentation

Data gathered from the instrumentation system will serve two purposes: a) to monitor the health of the propulsion system and b) to support quantity gauging of the propulsion system fluids and propulsion operations. Many of these instruments would perform both functions. The data will also be used for hazard controls and fault detection, isolation, and recovery (FDIR).

Health monitoring has functions of detecting any degradations of propulsion operation, including fluid resupply processes. The instrumentation will also monitor system performance and dynamic behaviors by checking for complex behaviors and interactions (e.g., excessive noise, repetitive high-speed event such as thruster pulsing, spikes, and level shifts).

- Valves failing opening/closing, valve leak, and component leakage will be assessed by monitoring pressure changes within the feedlines and manifolds.
- Chamber pressure and temperature can be used to monitor thruster valve leak/ performance.
- Pressure and temperature sensor performance and health can be assessed by monitoring data over time and by comparing redundant sensors to each other.

Quantity-gauging and supporting propulsion operations and resupply:

- Pressure and temperature on helium tanks and propellant tanks can be used for quantity-gauging during propulsion operations and refilling operations (P-V-T)
    - Thruster ON times can be used for quantity gauging as well, coupled with characterized thruster impulse cycled, commonly referred to as bookkeeping quantity gauging.
- Propellant tank pressures can be used to monitor tank pressure differentials. When the differential reading occurs, the iso valves on the propellant common manifold can be opened to balance the pressures between the tanks, if needed.
- Helium manifold pressure measurement is used to provide feedback, to control helium valve for regulating propellant pressure.

5.9.1 Redundancy of Instrumentation

Most instrumentation will be redundant for meeting 1-FT for its function. Instrumentation for quantity gauging, leak detection, fluid refill, and engine-firing operations (except for instrumentation on thruster) will be redundant. For a case of using non-redundant instrumentation, if a non-redundant sensor fails, sensors at other locations may be used to provide readings to confirm the sensor failure and interpret data needed.

Some measurements may require three sensors to read the same data of interest (e.g., helium tank pressure) for a voting logic process. For example, if one pressure transducer on a propellant tank (1-FT) fails, reading of the two remainder transducers should be able to point out an incorrect reading of the failed transducer, since the two remainder transducers would provide correct readings. This logic can be used for voting logic to support FDIR. Some readings may only need 2 pressure sensors to meet redundancy for 1-FT. In the event of a discrepancy between readings of the two sensors, a reading from a sensor instrumented on another component can be used to identify the outlier. Details of each situation will be addressed in future work. Currently, though, all 3 sensors will read the same data.

Instrumentation and redundancy described are needed for health monitoring and operations of the propulsion system. Thermal and Avionics may have some separate/overlapping instrumentation and redundancy requirements, with respect to propulsion (e.g., thermal is responsible to keep propellant tank temperature within a certain range, tank skin temperature sensors to be provided by thermal can be used for propulsion to gauge propellant on the tank). Understanding and addressing the interfaces and responsibilities of instrumentation among the three disciplines is needed to avoid unnecessary overlap requirements and/or to avoid having incomplete instrumentation to monitor performance and health of the interrelated propulsion, avionics, and thermal subsystems.

5.9.2 Types of Instrumentation

Several types of instrumentation are considered for TH RCS propulsion. They are described as follows:

- Pressure transducers will be used for all pressure readings.
- For temperature reading, there are two common types of temperature sensors used on spacecraft propulsion systems - resistance temperature detector (RTD) and thermocouples (TCs).
  - RTDs will be used for all temperature readings. RTDs will be used on component body surface [skin] temperature. RTDs can also be installed to read inline fluid temperature.
  - Most of propulsion components will be maintained at their operating temperature range, except for during refilling [e.g., helium gas could be temporarily overheated due to its pressure rise in TH tank], by using insulation, heaters, etc. The thermal conditioning and temperature readings will be provided by Thermal subsystem.
- Each iso latch valve will have a valve position indicator (VPI) to report the status of the valve operations. Employing redundant VPI for valves will be assessed in future.

– This is an example of the need for having valve positioning indicator: Upstream and downstream pressures differences of an iso latch valve can be used to detect flow through that valve at opening position; however, when these pressures are the same, it is not clear to confirm whether the iso valve is opened or closed, unless it has a VPI.

5.9.3 Helium Pressurization Assembly Instrumentation

Instrumentation within the helium pressurization assembly of the oxidizer side is shown in Figure 5.9.

- Triple pressure sensors are required for voting logic on the helium tank pressure measurement.
- Triple RTD temperature readings of the helium gas at the tank inlet are used to support the helium refill process. Depending on the method of monitoring thermal conditions, Thermal subsystem would have the tank skin readings. The performance of the propulsion subsystem does not need to have the skin temperature measurement otherwise.
- Triple pressure readings are used on the helium line manifold. The readings will be used for the helium control valve regulating the propellant tank pressure. It may be possible to use dual pressure (single redundant) transducers, as opposed to triple, as pressure readings from a propellant tank could be used to identify a faulty pressure sensor. This would meet 1-FT for instrumentation. However, the check valves upstream of the tanks could interfere with the interpretation of the information, due to the potential pressure drop across the check valve.

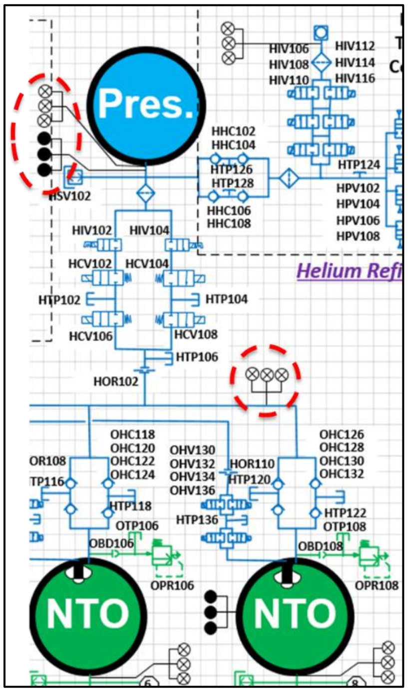


Figure 5.9: Instrumentation on Pressurization Assembly

5.9.4 Helium Refilling Assembly Instrumentation

Instrumentation within the helium refilling assembly of the oxidizer side is shown in Figure 5.10.

- Triple pressure readings will be used to confirm of receiving helium from the supply vehicle. The readings can be used to detect leaks..
- Pressure measurement on the lines to verify the valve opening is not needed since the valve has a position indicator.
- The supply vehicle will refill helium with a gradual increase in pressure.
  - At the beginning of the transfer, the HT helium tank pressure would be ~700 psia while the helium pressure of the supply vehicle could be ~6000 - 8000 psia if the transfer uses a pressure fed (i.e., pressurize-equalization) method.
  - High pressure gradient causes fast helium flow and rapid compression of gas with the receiver tank, which could result in excessively high temperature within the receiver helium tank.

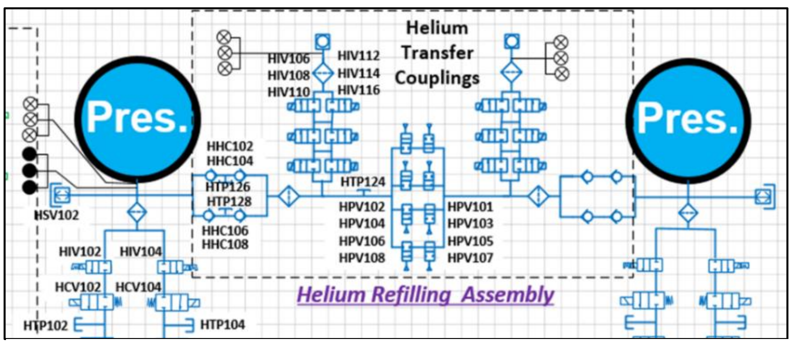


Figure 5.10: Instrumentation on Helium Refilling Assembly

5.9.5 Propellant Refilling Assembly Instrumentation

Instrumentation within the propellant refilling assembly of the oxidizer side is shown in Figure 5.11.

- Triple pressure readings are at the fluid transfer couplings for monitoring leak and confirming of receiving propellant from the supply vehicle.
- Pressure measurement on the lines to verify the valve opening is not needed since the valve has a position indicator. However, pressure readings may be needed to monitor the leakage across the valve seat. This requirement will be addressed in future work.
- The propellant tank pressure reading would also be used for monitoring the propellant transfer.

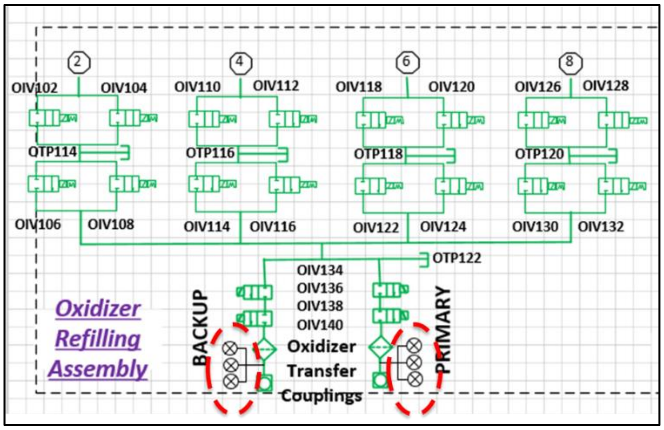


Figure 5.11: Oxidizer Tank Ullage Gas Venting Assembly

5.9.6 Tank Ullage Venting Assembly Instrumentation

Instrumentation within the tank ullage venting assembly of the oxidizer side is shown in Figure 5.12.

- Triple in-line sensors (i.e., RTDs) on the venting manifold (at the outermost outlet leg) are used to monitor the venting gas. Propellant vapor would turn to liquid and freeze if the temperature gets too low.
- Pressure reading on the venting manifold is not needed.
- An orifice at the outlet is not needed since it is desirable to have the venting near vacuum to prevent the backward flow into other tanks.

It should be noted that the liquid/gas phase separator may not work properly if there is a large pressure gradient between the propellant tank and the venting manifold. Hence, an orifice may be needed at the outlet of the separator.

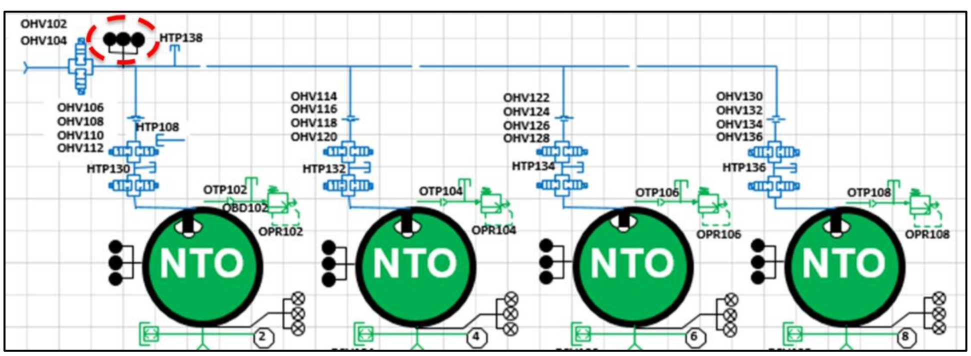


Figure 5.12: Instrumentation on Tank Ullage Venting Assembly

5.9.7 Propellant Tank Instrumentation

Instrumentation within the propellant tanks of the oxidizer side is shown in Figure 5.13.

- Triple tank pressure readings are for gauging propellant and monitoring propellant conditions. In an event of pressure imbalance among the prop tanks pressure, the iso valves on the feedline can be opened for equalizing their pressures.
- Triple in-line propellant temperature sensors are used to gauge propellant during tank refilling.

It should be noted that tank skin temperature sensors (not shown) to be provided by Thermal subsystem are used to monitor the propellant temp, provided that the influence of the tank wall on the temperature of the propellant is considered.

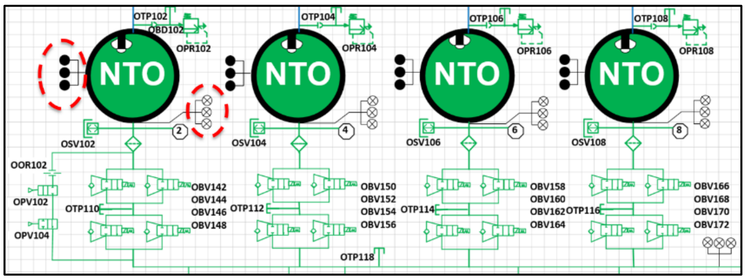


Figure 5.13: Instrumentation on Propellant Tanks

5.9.8 Propellant Feedline and Thrusters Instrumentation

Instrumentation within the propellant feedline and thrusters is shown in Figure 5.14.

- Triple pressure readings on the common propellant manifold are to monitor the pressure in case that the back pressure relief does not work, and to provide system diagnostics.
- Triple pressure readings on thruster manifold are to monitor for leaks through the thruster valve. A venturi will be used to the control flow rate to the thruster..
- It is assumed that there are single pressure and chamber temperature readings, provided by the thruster developer. The readings are used to monitor the engine health/performance. Chamber temperature can be used to monitor propellant leak. Contingency of engine usage if either of these sensors has failed will be addressed in future work.

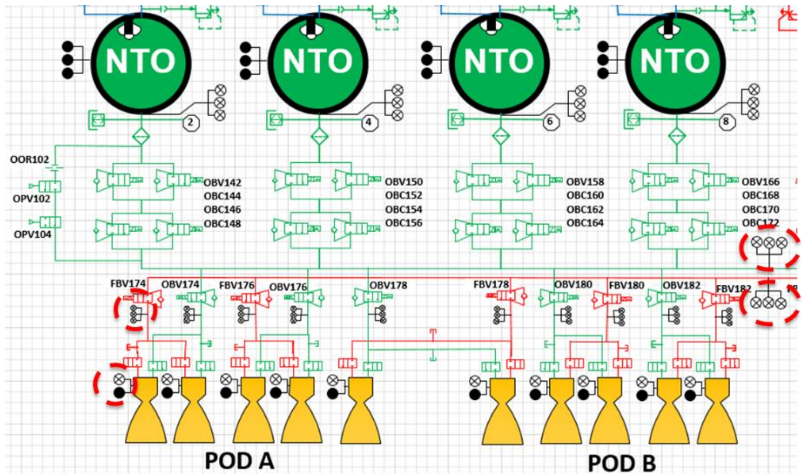


Figure 5.14: Instrumentation on Propellant Feedline and Thrusters

5.10 Propulsion System Test ports

Test ports have several purposes: a) to check for internal component leak (e.g., valves, etc.) and external leaks from components (if relevant) and/or a section/portion of the line system (e.g., weld, fitting, etc.); b) to provide access flow conditions for valve function tests (e.g., pressurizing an upstream valve to verify valve opening/closing within acceptance criteria); and c) to test for flow obstructions, such as from foreign object debris (FOD).

Assumptions on the test ports are as follow:

- Valves have enough cycle life margin included for performing tests; otherwise, some additional test ports may be needed to reduce valve cycles used during tests. Some test ports, assigned for testing functions, can be used to reduce valve cycle life of other valves as appropriate. For example, Test Port HTP102 on the helium control valve line is used for leak checks and functional testing of HCV102. THP102 is then used to supply helium for testing HCV106. That way, HCV102 does not need to be open while testing HCV106.
- Either test port couplings or service valves will be used for test ports to meet 2-FT (i.e., 3 barriers) against external leakage.
- All parent metal pyro valves go through acceptance testing; hence, leak checks of the valves are not required.
- All solenoid valves (e.g., helium control valve, thruster valves, etc.) can be held open for extended time (> 5 minutes) while testing other valves in a same flow circuit. A solenoid valve normally requires high energy to initiate valve opening, then drop a low energy level to keep it opening. Subsequently, the coil can be energized for an extended period without being over heated.

5.10.1 Helium Pressurization Assembly Test Ports

Test ports within the helium pressurization assembly are shown in Figure 5.15. The locations and descriptions of the test port functions are as follows.

- Test port HTP102 will be used for leak checks of the helium isolation latch valve HIV102 and helium control valve HCV102. Function test of HCV102 will also use HTP102. HIV102 would be open while testing HCV102. For the tests, a helium source will be supplied through helium service valve HSV102.
- Similar to the purposes of Test port HTP102, Test port HTP104 will be used for leak checks of HIV104 and HCV104.
- Test port HTP106 will be used for leak checks and functional testing of helium control valve HCV106 and HCV108. Helium will be supplied through Test port THP102 and THP 104 for testing HCV106 and HCV108, respectively. As such, the upstream valves will not be kept open during the test.
- Sets of Test Port HTP108 and HTP110, THP112 and HTP114, etc. are located between two check valves on each pair in series – OHC102 and OHC104, OHC106 and OHC108, etc. because of leak tests required for an individual check valve. Helium will enter through oxidizer service valve OSV102 to check leak on both OHC104 and OHC108 with Test Port HTP108 and HTP110, respectively. Check valves in series OHC102 and OHC106 can be built in the same unit and test port between them HTP108 can also be built in on the unit as well. For testing check valves OHC102 and OHC104, helium will be supplied through THP108 and HTP110, respectively. The same description of function is applied for check valves upstream of other tanks.

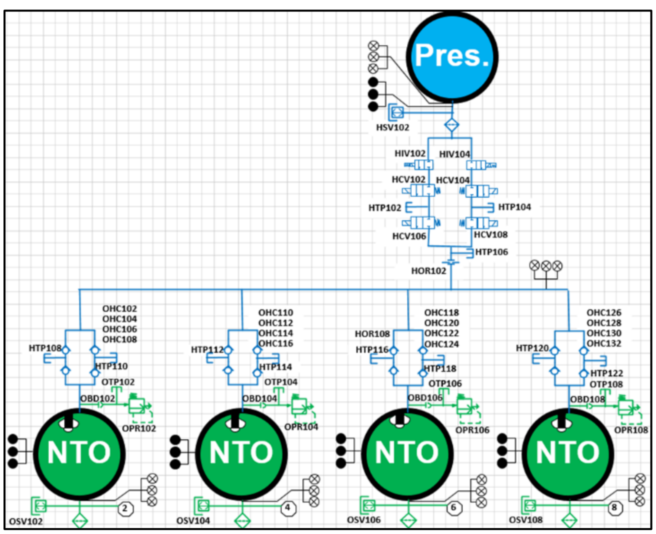


Figure 5.15: Test Ports on Helium Pressurization Assembly

5.10.2 Liquid Propellant Subsystem Test Ports

Test ports within the liquid propellant subsystem (which includes propellant tanks, feedlines, and thruster pods) are shown in Figure 5.16. The locations and descriptions of the test port functions are as follows.

- Oxidizer Test Port OTP102 is located between an oxidizer burst disk OBD102 and an oxidizer pressure relief OPR102. The test port will be used for leak checks of the burst disk and provide helium source for checking the leak and functional testing of OPR102. The same description is applied for oxidizer test ports between the burst disks and the oxidizer pressure relief on other tanks.
- Oxidizer pyro valves OPV102 (initially open) and OPV104 (initially closed) on the primming line will not need a leak check since they are parent metal sealed and already past acceptance testing.
- Oxidizer Test Port OPT110 is placed on the center of figure-eight configuration of oxidizer tank isolation latch valves (with back pressure relief) OBV142, OBV144, OBV146, and OBV148. The test port will be used for leak checks of OBV142 and OBV144 with helium supplied for test through OSV102. The same description of the test port is also applied for Test Ports – OPT112, OPT114, and OPT116.
- Oxidizer Test Port OPT118 will be on the common feed line manifold. The test port will be used to leak check and functional tests of the remaining valve pair OBV146 and OBV148, so on. Helium will enter OPT 110 for testing OBV146 and OBV148 and so on.
- Oxidizer iso latch valve (with back pressure relief) OBV173 on thruster manifold line and thruster valve can be tested as follow: for testing OBV173, helium will be supplied through OTP118. OBV173 is closed for the leak check while the thruster valve is kept open. For testing leak and function of the thruster valve, OBV173 will be open. That way there is no need of a test port on the thruster manifold. When a thruster throat plug is installed on one thruster, flow resistance, FOD test can be performed on other thruster since the feedline of the pair thrusters have the same iso-valves.

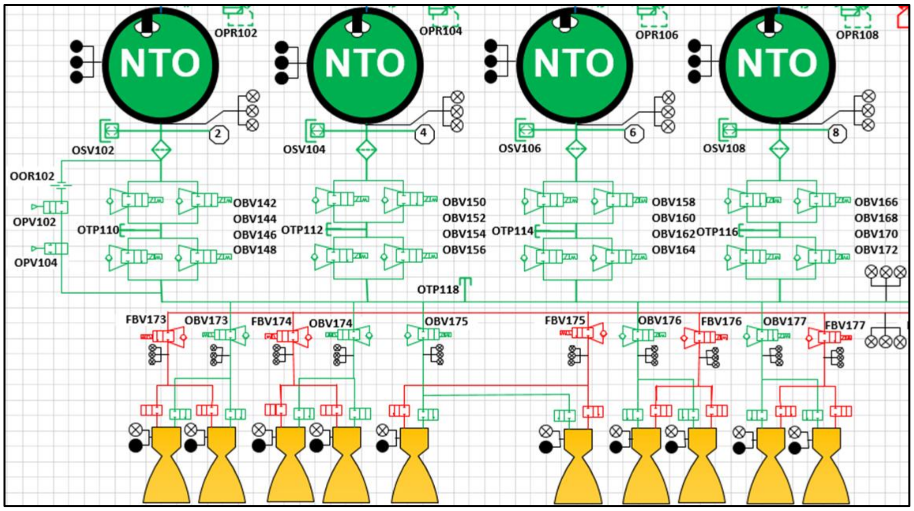


Figure 5.16: Test Ports on Propellant Tanks, Feedlines, and Thruster Pods

5.10.3 Helium Refilling Assembly Test Ports

Test ports within the helium refilling assembly are shown in Figure 5.17. The locations and descriptions of the test port functions are as follows.

- Test Port HTP126 and HTP128 are located between two check valves on each pair in series – HHC102 and HHC104, OHC106 and OHC108, respectively, since leak testing is required for an individual check valve. Helium will enter through oxidizer service valve HSV102 to check leaks on both HHC102 and HHC106 with Test Port HTP126 and HTP128, respectively. Check valves in series HHC102 and HHC104 can be built in the same unit and the test port between them HTP126 can also be built in on the unit as well. For testing check valves HHC104 and HHC108, helium will be supplied through THP126 and HTP128, respectively, while Test Port HTP124 will be used for this leak check.
- Helium isolation valves, HIV106, HIV108…, and HIV116, will be tested in a pair for leaks. For the leak check of a pair HIV110 and HIV116, they are in the closed position while all remaining iso valves on the lines HIV106, HIV112, HIV108, and HIV114 are open. Pressure decay will be observed with helium initially supplied through Test Port HTP124. Similarly, other pairs HIV108/HIV114 and HIV106/HIV112 will be tested in a similar manner.

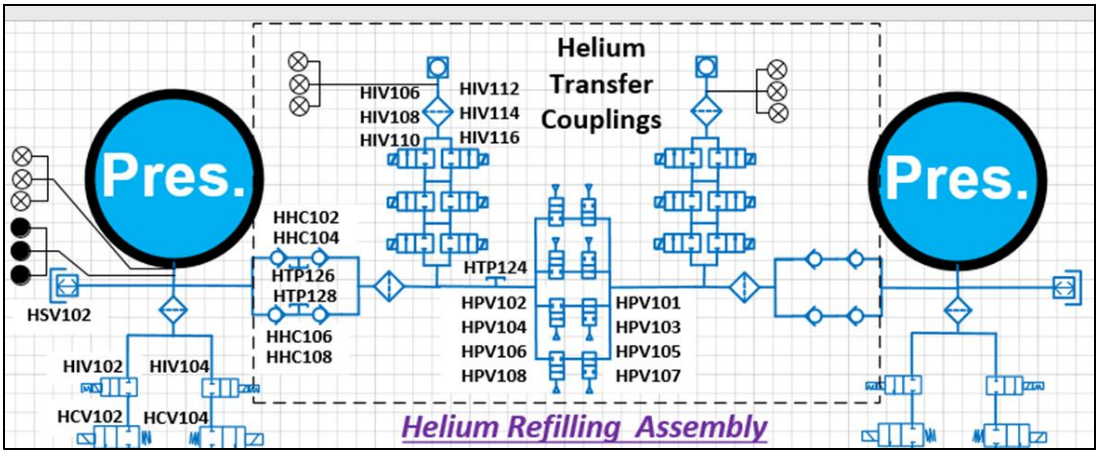


Figure 5.17: Test ports on Helium Refilling Assembly

5.10.4 Oxidizer Refilling Assembly Test Ports

Test ports within the oxidizer refilling assembly are shown in Figure 5.18. The locations and descriptions of the test port functions are as follows.

- Oxidizer Test Port OPT114 is placed on the center of figure-eight configuration of oxidizer iso latch valve OIV102, OIV104, OIV106, and OIV108. The test port will be used for leak checks of OIV102 and OIV104 in pair with helium supplied for test through OSV102. The same description of the test port is also applied for Test Ports – OPT116, OTP118, and OTP120.
- Oxidizer Test Port OPT122 will be on the common line manifold of the oxidizer refilling assembly. The test port will be used to leak check the remaining valve pairs OIV106/OIV108, OIV114/OIV116, and OIV130/OIV132. Helium will enter OPT114 for testing OIV106 and OIV108, with similar helium paths for other testing pairs.
- Oxidizer Test Port OPT122 will be also used for individual leak check of OIV134, OIV136, OIV138, and OIV140 on the transfer coupling legs (e.g., for the leak check of OIV134 on the primary transfer coupling leg, the valve is closed while all other three valves are open with a cap is installed on the transfer backup leg). Helium will be supplied through this test port. The pressure decay then will be observed.

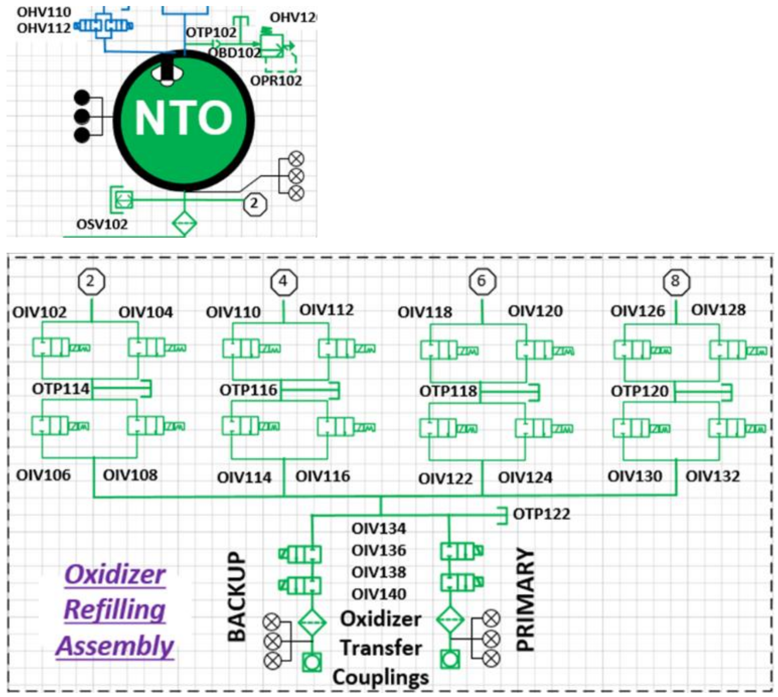


Figure 5.18: Test Ports on Oxidizer Refilling Assembly

5.10.5 Tank Ullage Venting Assembly Test Ports

Test ports within the tank ullage venting assembly are shown in Figure 5.19. The locations and descriptions of the test port functions are as follows.

- Helium Test Port HPT130 is placed on the center of figure-eight configuration of oxidizer/helium [mixed ullage gas] iso valve OHV106, OHV108, OHV110, and OHV112. The test port will be used for leak check of OHV110 and OHV112 in pair with helium supplied for test through OSV102. The same description of the test port is applied for Test Ports HTP132, HTP134, and HTP136.
- Oxidizer Test Port HTP138 will be on the common manifold of the ullage venting assembly. The test port will be used to leak check of the remaining valve pairs OHV106/OHV108, OHV114/OHV116, OHV122/OHV122, and OHV130/OHV132. Helium will enter OPT130 for testing OHV106 and OHV108, with similar helium paths for other testing pairs.
- Oxidizer Test Port HPT138 will be also used for leak check of OHV102 and OHV104. Helium will be supplied through this test port. The pressure decay then will be observed.

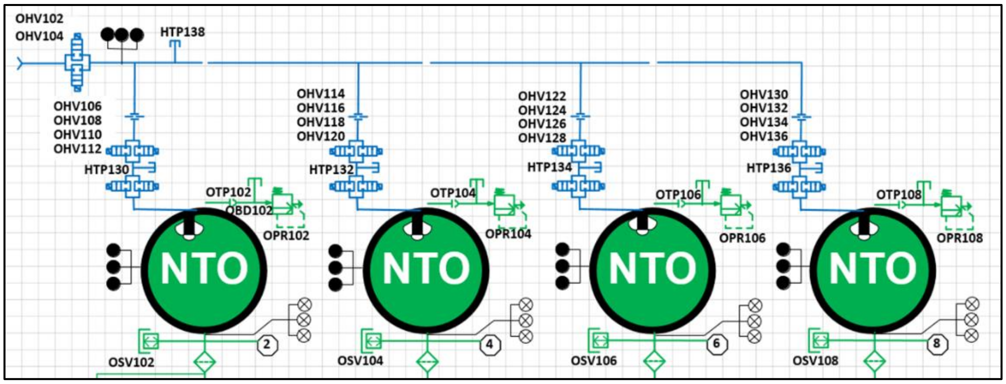


Figure 5.19: Test Ports on Tank Ullage Venting Assembly

5.11 Master Equipment List (MEL) for TH Forward & Aft RCS Systems

To support the government reference conceptual TH design performed by the NASA Habitation Systems Development Office, the MEL for the forward and aft propulsion systems with the pressure-regulated concept has been created. The propulsion MEL has been then rolled up to the MEL at the TH element level. The list includes per-component count, unit mass, and mass growth allowance (MGA). Component listings are grouped by sub-system assembly. The propulsion MEL for the pressure-regulated concept is in Appendix B.

5.11.1 Propulsion Component Mass Estimate

The Propulsion Component Branch, ER14, of MSFC Propulsion Department provides unit mass for most components referenced to flight-qualified hardware. Table 5.1 shows a detailed breakdown of components for propulsion subsystem assemblies and available commercial components on which the unit mass is based. The data is used to generate the MEL for the TH propulsion systems.

Table 5.1: Component Mass Estimate on Forward RCS System

Components	Unit Mass (kg)	FORWARD RCS Oxidizer Side Quantity	FORWARD RCS Fuel Side Quantity	AFT RCS Oxidizer Side Quantity	AFT RCS Fuel Side Quantity
Helium Refilling [Resupply] Assembly					
Helium Half-Fluid Transfer Couplers (HFTC)	6.8	1	1	1	1
Helium Filters	0.25	2	2	2	2
Helium Isolation Latch Valve	0.34	6	6	6	6
Helium Pyro Valves	0.32	4	4	4	4
Check Valves	0.23	4 (2 Pairs)	4 (2 Pairs)	4 (2 Pairs)	4 (2 Pairs)
Helium Test Ports (bet. two check valve in series)	0.12	2	2	2	2
Helium Test Port	0.12	1	1	1	1
Pressure Transducer	0.1	3	3	3	3
Helium Pressurization Assembly					
Helium Tank	7.06	1	1	1	1
Helium Service Valve (Fill/Drain)	0.12	1	1	1	1
Helium Filters	0.5	1	1	1	1
Helium Isolation Latch Valves	1.13	2	2	2	2
Helium Control Solenoid Valves	1.25	4	4	4	4
Helium Orifice	0.01	1	1	1	1
Helium Check Valves	0.23	16 (8 pairs)	16 (8 pairs)	16 (8 pairs)	16 (8 pairs)
Helium Test Ports	0.12	3	3	3	3
Helium Test Ports (bet. two check valve in series)	0.12	8	8	8	8
Pressure Transducer on pressurant lines	0.1	3	3	3	3
Pressure Transducers on pressurant tank	0.1	3	3	3	3
Temperature sensor on pressurant tank	0.1	3	3	3	3
Propellant Tanks & Propellant Common Feedline Manifold					
Propellant Tank	6.91	4	4	4	4
Propellant Burst Disk	0	4	4	4	4
Test Ports (bet. burst disk and pressure relief)	0.3	4	4	4	4
Propellant Pressure Relief Valve	2.27	4	4	4	4
Propellant Service Valve (Fill/Drain)	0.21	4	4	4	4

Table 5.1: Component Mass Estimate on Forward RCS System (Continue)

Components	Unit Mass (kg)	FORWARD RCS Oxidizer Quantity	FORWARD RCS Fuel Side Quantity	AFT RCS Oxidizer Quantity	AFT RCS Fuel Quantity
Propellant Filter	0.3	4	4	4	4
Orifice (on the propellant priming line)	0.1	1	1	1	1
Propellant pyro valve	0.32	2	2	2	2
Propellant iso latch valve with back pressure relief	0.73	16	16	16	16
Test Ports (at center of figure-eight valve configuration)	0.21	4	4	4	4
Test Port	0.21	1	1	1	1
Pressure Transducer on Feed line	0.1	33	33	33	33
Pressure Transducers on tanks	0.1	12	12	12	12
Temperature sensor on tanks	0.1	12	12	12	12
Thruster Manifold and Thruster					
Propellant iso latch valve with back pressure relief	0.73	10	10	6	6
Thrusters	4.6	20		12	
Pressure Transducers on thruster	0.1	30	30	18	18
Propellant Tank Ullage Venting Assembly					
Liquid/Gas Phase Separator	0.67	4	4	4	4
Iso latch valves (Figure-eight configuration)	0.73	16	16	16	16
Iso latch valves	0.73	2	2	2	2
Test Ports (at center of figure-eight valve configuration)	0.21	4	4	4	4
Test Port	0.21	1	1	1	1
Orifice	0.01	4	4	4	4
Propellant Refilling (Resupply) Assembly					
Propellant Half-Fluid Transfer Couplers (HFTC)	6.8	2	2	2	2
Propellant Filters	0.3	2	2	2	2
Propellant Iso Latch Valve (in Series)	0.73	4	4	4	4
Propellant Iso latch valves (Figure-eight configuration)	0.73	16	16	16	16
Propellant Test Ports (at Center of Figure-Eight Valve Configuration)	0.21	4	4	4	4
Propellant Test Port	0.21	1	1	1	1
Pressure Transducer	0.1	6	6	6	6

Component selections are based on the operational conditions of pressurant and propellant pressures of approximately 4500 psia and 250 psia, respectively. Propellant system line sizes are assumed around 3/8” to ½” diameter. The selections are meant to be rough approximations of the hardware needed. Analyses will be performed as a future work, for determining the adequacy of these items to meet system requirements such as flow rate, etc. The MGA percentage, which accounts for the historically predicted mass change as the engineering fidelity increases, is added to the component mass. The assigned percentage is consistent with the guidelines provided in ANSI/AIAA S-120A-2015 (R 2019) [13]. It should be noted that unit mass of four items (i.e., liquid/gas phase separator, half liquid transfer coupler, helium pressurant tank, and propellant tank) is not derived from the flight hardware but rather estimated.

The phase separator is still an early phase of technology development [14,15]. Sizing the component depends on the operation conditions, flow rate, and allowable time for venting the ullage gas. Due to the lack of data, the mass of the liquid/gas phase separator for this application can only be approximated. The unit mass is assumed to be 10% of the propellant tank dry mass. MGA of 25% is applied to the estimate, to account for this mass change. It is a similar challenge to determine the mass of the passive-half FTC on HT side. Based on technical interchanges (see Attachment A) with experts at Kennedy Space Flight Center, and Johnson Space Center, who are specialized on the field of in-space fluid transfer technologies, “it seems reasonable that each half of the fluid coupler could be around 15lbm [6.8kg] or less, depending upon preferred design features”. Mass of the secondary structure for mounting the FTC is accounted under “Mounting/Install Hardware” (See Appendix B).

The propellant and helium pressurant tanks are sized using a MSFC Advanced Concepts Office (ACO) Propulsion Tool (Version 7) [16]. The methods for calculating the tanks sizes and masses will be discussed in the next section. The results of these calculations will be also presented.

5.11.2 Calculation of Propellant and Helium Tank Sizes and Masses

The ACO Propulsion Tool was written in Excel by the ACO at MSFC. The tool uses fluid thermal data to size the tanks for spacecraft pressure-fed propulsion systems. It has features for calculating propellant and pressurant consumption, by specifying propellant conditions and propulsion operations (e.g., vehicle mass, propellant type, pressure, temperature, total impulse, Isp, etc.). These results are then used to size the tanks. The tool then determines the tank dry masses, by either scaling from existing tanks or using correlations for given geometries (sphere, cylindrical, etc.), fabrication methods, tank materials (metals, COPV, etc.). The calculation sheets also approximate a rough mass of the fluid plumbing system based on a percentage (provided by users) of the tank masses.

For the TH propulsion conceptual design, the propellant quantities are obtained from Table 2.1. The tank storage capacity will include additions of 15%, 10%, and 1% for propellant residual, reserve, and mixture ratio bias error, respectively. Design analysis for the bi-propellant system, MON3/MMH, with a mixture ratio around 1.65 would lead to a small variation in oxidizer and fuel volume requirements. Most spacecraft, including the TH RCS system, typically end up of having the same tank size for both propellants, which can reduce propellant tank procurement costs. Table 5.2 shows fluid conditions and operation parameters used to size propellant and helium pressurant tanks.

Table 5.2: Fluid Conditions & Operation Condition for Sizing Tanks

Fluid Conditions /Operation Parameters	Value
Initial Pressurant Tank Pressure	4500 psia
Final Pressurant Tank Pressure	500 psia
Initial/Final Pressurant Tank Temperature	530 R
Initial/Final Propellant Tank Pressure	250 psia
Initial/Final Propellant Tank Temperature	530 R
Propellant Mixture Ratio	1.65
Initial Propellant Ullage (volume tank percentage)	3%

The results from the ACO Propulsion tool are shown on Figure 5.20. As previously stated, the propellant tank mass is scaled from Space Shuttle RCS tank data [12] using the PVW tank scaling method, which is the tank mass being proportional to the pressure and volume ratios between the two tanks. The tanks are made of titanium (Ti-3Al-4V forged). They have a complex PMD system to keep pressurant and propellant vapor from exiting the tanks as the liquid propellant is fed to the thrusters. The size of the helium tanks is calculated based on the propellant tank sizes and the fluid operating conditions. The tanks are COPVs, made of carbon fiber (T-1000), with the inner liner being Inconel 718. All tanks are spherical. An MGA of 15% has been applied to the tank mass. The mass of the plumbing system is assumed to be 50% of all combined tank masses.

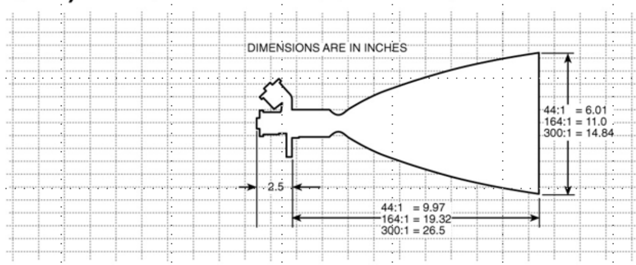
	Fuel Tanks			
Number of Fuel Tanks	4			
Fuel Tank Radius (meters)	0.75	Only for Cylindrical Tanks		
Fuel Tank Geometry	Scaling based on SS RCS Tank	dropdown list		
Fuel Tank Material	Titanium (Ti-6Al-4V, Forged)	dropdown list		2
Factor of Safety	1.4			
Material Correction Factor	0.95			
Temperature Correction Fac	0.97			
Fuel Tank Operating Pressu	250	Psi	1.72E+06	Pa
Fuel Tank Diameter	0.585	m	1.920	ft
Fuel Tank Barrell Length	NA	m	NA	ft
Fuel Tank Total Height	0.585	m	1.920	ft
Fuel Tank Mass (x1)	**6.906**	**kg**	**15.226**	**lb**
Total Fuel Tank Mass	**27.626**	**kg**	**60.904**	**lb**
	Oxidizer Tanks			
Number of Oxidizer Tanks	4			
Oxidizer Tank Radius (mete	0.5	Only for Cylindrical Tanks		
Oxidizer Tank Geometry	Scaling based on SS RCS Tank	dropdown list		
Oxidizer Tank Material	Titanium (Ti-6Al-4V, Forged)	dropdown list		2
Factor of Safety	1.4			
Material Correction Factor	0.95			
Temperature Correction Fac	0.97			
Ox Tank Operating Pressure	250	Psi	1.72E+06	Pa
Oxidizer Tank Diameter	0.585	m	1.920	ft
Oxiizer Tank Barrell Length	NA	m	NA	ft
Oxidizer Tank Height	0.585	m	1.920	ft
Oxidizer Tank Mass (x1)	**6.906**	**kg**	**15.226**	**lb**
Total Oxidizer Tank Mass	**27.626**	**kg**	**60.904**	**lb**
	Pressurant Tanks			
Number of Pressurant Tanks	2			
Press. Tank Radius (meters)	0.20	Only for Cylindrical Tanks		
Pressurant Tank Geometry	Spherical	dropdown list		5
Pressurant Tank Type	COPV	dropdown list		
Liner Material	Inconel 718	dropdown list		
Overwrap Material	Carbon Fiber, T-1000	dropdown list		
Factor of Safety	1.5			
Material Correction Factor	0.95			
Temperature Correction Fac	0.97			
Pressurant Tank Pressure	4500	Psi	3.10E+07	Pa
Pressurant Tank Diameter	0.417	m	1.37	ft
Pressurant Tank Barrell Length	NA	m	NA	ft
Pressurant Tank Height	0.417	m	1.37	ft
Pressurant Tank Mass (x1)	**7.060**	**kg**	**15.564**	**lb**
Total Pressurant Tank Mass	**14.119**	**kg**	**31.128**	**lb**
	Feedlines / Fittings			
Estimation Method	Tank Mass Percentage	dropdown list		
Tank Mass Percentage	50.0%	If estimating by tank mass		
Feed Line Material	Stainless Steel (305 SS)	If estimating by pipe length		5
Material Correction Factor	0.95			
Temperature Correction Fac	0.97			
Factor of Safety	1.4			
Feed Line Mass	**34.685**	**kg**	**76.468**	**lb**

Figure 5.20: Tank Sizes and Masses Calculated from ACO Propulsion Tool

5.11.3 Thruster Selection for Propulsion Concept Design

Selection of RCS thruster is heavily dependent upon GNC requirements (e.g., MIB, thrust, etc.). The total impulse and Isp of the thruster represent the thruster capability and performance that must satisfy mission requirements (e.g., total thruster impulse for entire mission, system mass allocation, etc.). From technical exchanges (see Attachment B) with the GNC team, the Aerojet 110-lbf R-4D would be suitable to be used as a referenced RCS thruster for this concept design. Data for the R-4D [17] is shown in Figure 5.21. The thruster is commercially available and its operational characteristics and capabilities from test data (e.g., engine dynamics behavior, inlet pressure range) can be found in public domain literature. The engine data will be used to assess its applicability for the blowdown concept, which will be discussed in the later sections.

R-4D 490N (110-lbf) BIPROPELLANT ROCKET ENGINE



Design Characteristics

- Propellant . . . . MMH/NTO(MON-3)
- Thrust/Steady State 490N (110-lbf)
- Inlet Pressure Range . . . . 29.3–4.1Bar (425–60 psia)
- Chamber Pressure* . . . . 7.45 Bar (108 psia)
- Expansion Ratio 44:1, 164:1, 300:1
- Flow Rate* . . . . 158 g/sec (0.348 lbm/sec) (300:1)
- Valve . . . . Aerojet Solenoid, Single Coil, Single Seat
- Valve Power . . . . Various (46 Watts @ 28 Vdc Typical)
- Mass . . . . 44:1, 3.40 kg (7.5 lbm)
  . . . . 164:1, 3.76 kg (8.3 lbm)
  . . . . 300:1, 4.31 kg (9.5 lbm)
  - Engine . . . . 44:1, 2.49 kg (5.5 lbm)
    . . . . 164:1, 2.86 kg (6.3 lbm)
    . . . . 300:1, 3.40 kg (7.5 lbm)
  - Valve . . . . 0.9 kg (2.0 lbm)

*at Rated Thrust

Performance

- Specific Impulse* . . . . 44:1 = 300 sec (lbf-sec/lbm)
  . . . . 164:1 = 311 sec (lbf-sec/lbm)
  . . . . 300:1 = 315.5 sec (lbf-sec/lbm)
- Total Impulse Demonstrated
  . . . . 20,016,000 N-sec (4,500,000 lbf-sec)
- Total Pulses 20,781
- Minimum Impulse Bit . . . . 15.6 N-sec (3.5 lbf-sec)
- Demonstrated Steady State Firing . . . . 12,000 sec

Status

- Flight Proven

References

- AIAA - 2004 - 3694
- AIAA - 1980 - 1294
- AIAA - 1979 - 1331

Rev. Date: 5/24/05

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AEROJET

Figure 5.21: Aerojet 100-lbf R-4D Thruster Data Sheet

Although the R-4D thruster has various nozzle exit sizes, a small nozzle exit-to-throat area ratio of 44:1 is chosen to avoid a physical interference with the transit habitat structure. The Isp for the area ratio of 44:1 is 300 seconds. It is noted that GNC provided propellant estimate (shown in Table 2.1) using an Isp of 300 sec for a pressure regulated system, which matches the performance of this 44:1 R-4D thruster. For the human-rated mission, it is desirable to have chamber pressure readings and injector temperature sensors equipped on the thruster. The mass of the thruster is estimated as follows:

Table 5.3: R-4D Thruster Mass Breakdown

Engine mass of 44:1 exit area ratio	3.4 kg
Valves (Aerojet Solenoid, Single Coil, Single Seat)	0.9 kg
Pressure transducer (passive)	0.1 kg
Temperature sensor (assuming similar mass of the transducer)	0.1 kg
Total	4.5 kg

It should be noted that a mass budget of 4.6 kg is used for the R-4D on another flight-qualified spacecraft. Hence, the unit mass of 4.6 kg, instead of 4.5 kg, is used for the TH propulsion design as a conservative measure.

6 Blowdown Propulsion Concept

The pressure-regulated propulsion concept has been previously discussed in detail. In support of the propulsion trade study for the TH, the blowdown concept will be described in this section. Since the blowdown system is also a pressure-fed system, most of components between the two concepts have similar capabilities and functions. Differences in the sub-system assemblies will be appropriately described throughout this section.

In contrast to the pressure-regulated system, the entire helium pressurant in the blowdown system is stored within the propellant tanks. Hence, there will be no pressurization sub-system as seen on the pressure regulated system. When operating in blowdown mode, the tank pressure decreases as propellant is consumed. The lower bound of the tank pressure must be within the capability of the RCS thruster operation.

Both concepts are baselined using propellant PMD tanks. The purpose of a PMD is to keep the ullage gas inside the tank, while allowing liquid propellant to exit the tank. The helium in the propellant tanks for the blowdown would be recompressed as the tanks are refilled. Subsequently, both the helium refilling assembly and ullage venting assembly will not be needed. Theoretically, the pressurant gas inside the propellant tanks would never be replenished throughout the entire many-year mission. However, it is anticipated that a small amount of pressurant gas would be dissolved and/or entrained in the liquid during the mission. Therefore, it is envisioned that a small amount of helium gas can be resupplied during the propellant refilling process as needed. For the helium resupply requirement, the supply vehicle must be capable to transfer the gas (i.e., purging the transfer line with helium) at the end of the transfer process.

6.1 Flow Schematic of TH Blowdown Propulsion Concept

Figure 6.1 shows the differences in the flow schematics between the pressure-regulated and blowdown for the forward RCS propulsion system. The helium pressurization, helium refilling, and ullage venting assemblies are removed from the pressure-regulated system for the blowdown. They are shaded with light blue.

Burst disk and pressure relief valve components shown in the pressure-regulated flow schematic (i.e., shaded with light yellow) are connected to the propellant tanks. The intent of the pressure relief is to protect against an over-pressurization event (e.g., high-pressure helium leaking to the propellant tank). The pressure relief feature is not required for the blowdown because of no extremely high-pressure source. In an event of an over-pressurization during the propellant loading, it is assumed that the supply vehicle would provide the pressure relief feature function.

The forward and aft TH RCS propulsion systems are shown on Figures 6.2 and 6.3.

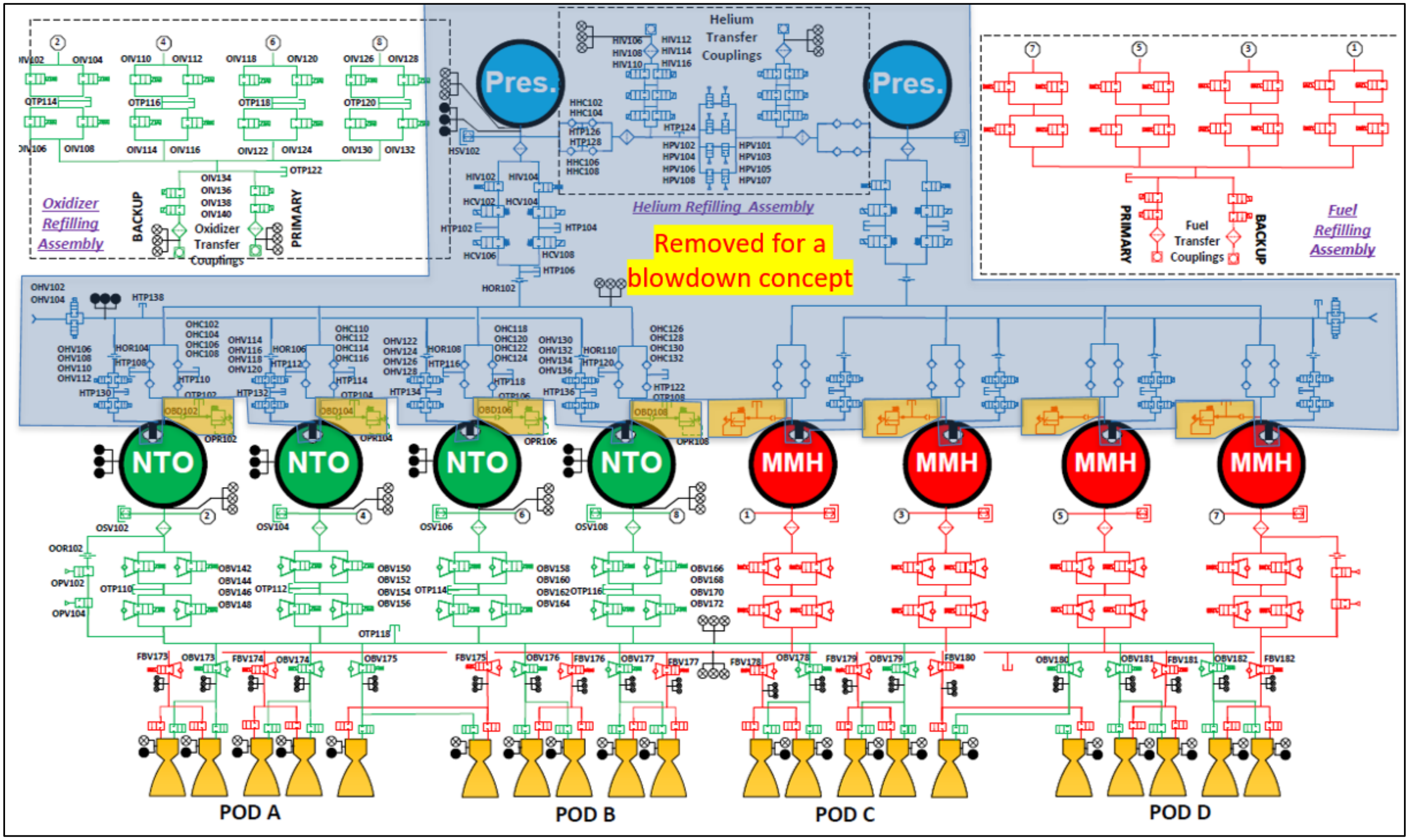


Figure 6.1: Differences in Flow Schematics between Pressure-regulated and Blowdown Propulsion Concepts

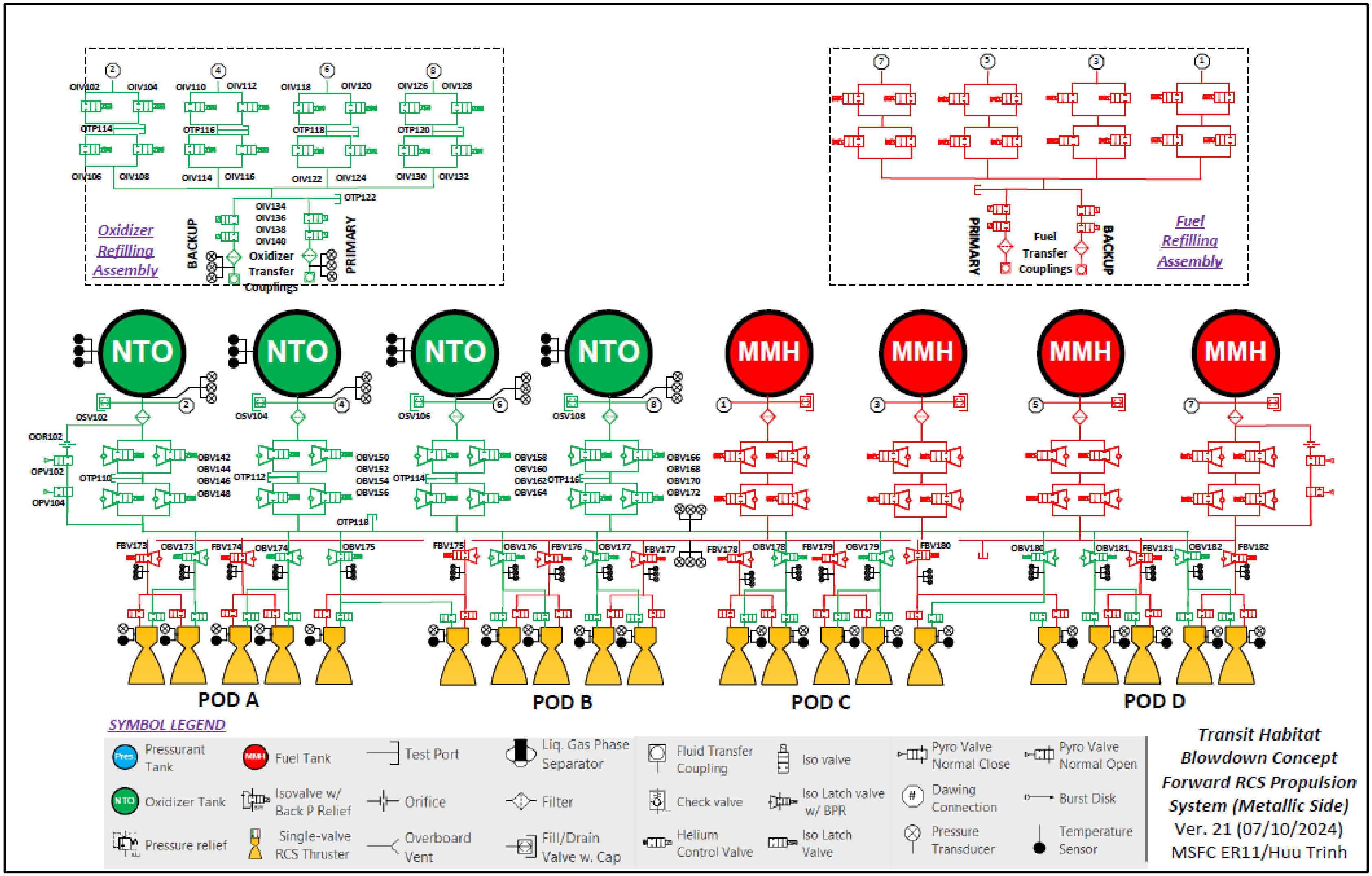


Figure 6.2: Flow Schematic of Blowdown Concept for Forward TH RCS Propulsion

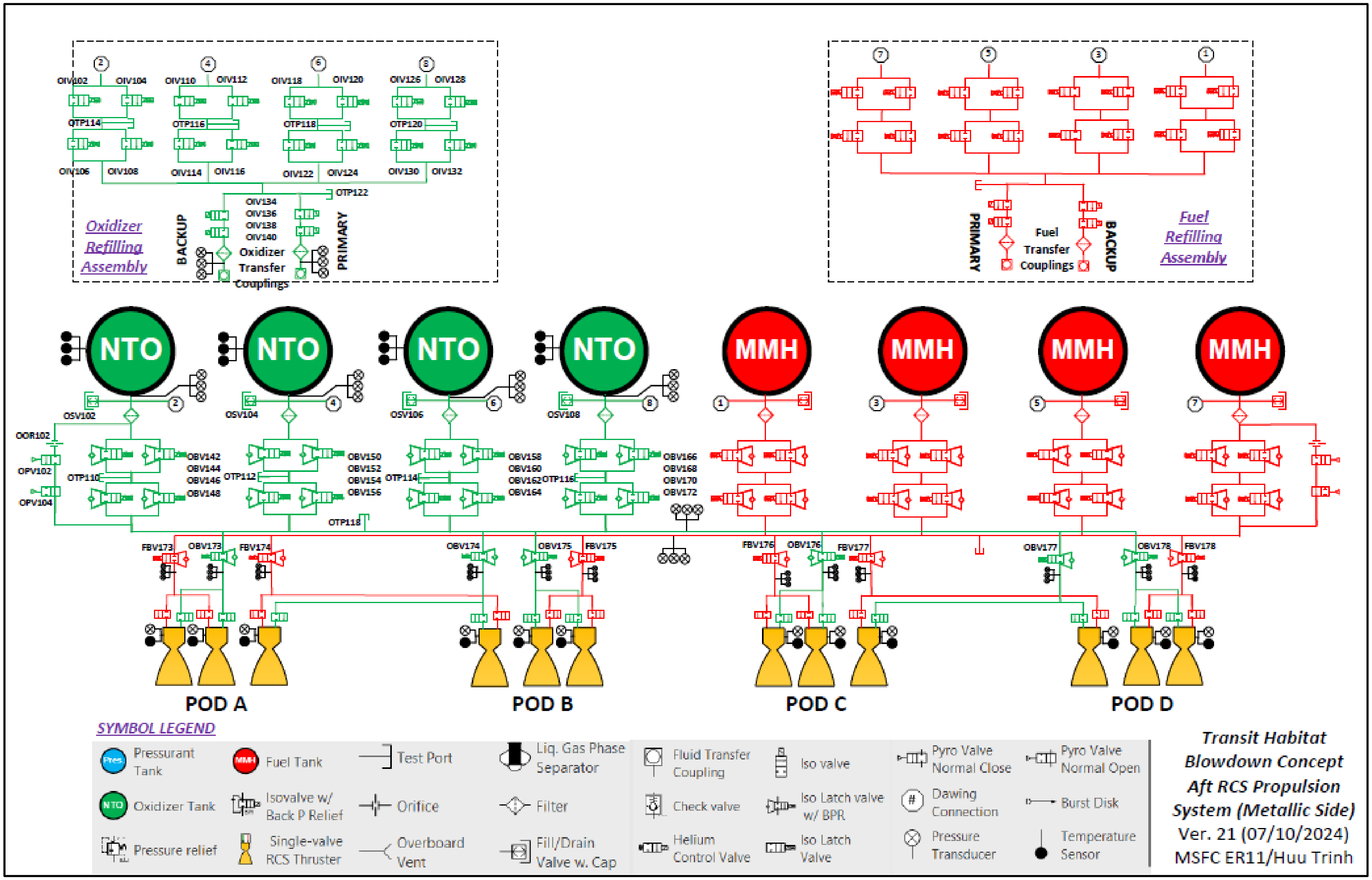
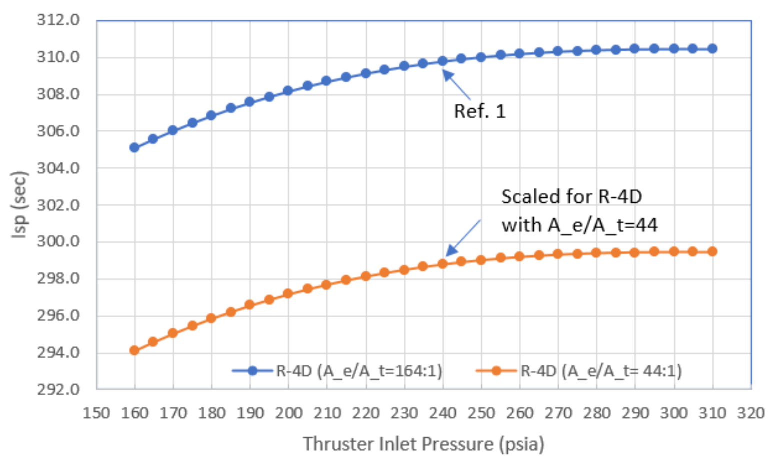


Figure 6.3: Flow Schematic of Blowdown Concept for Aft TH RCS Propulsion

6.2 Estimate of Propellant Increase for Blowdown Propulsion Operation

The Aerojet R-4D has operated in blowdown mode on flight missions [18]. The thruster was qualified to a maximum inlet pressure (P_{in}) of 310 psia. The engine test results showed that it could operate with the inlet pressure down to 160 psia before experiencing chug. Hence, the inlet pressure range between 170 psia and 310 psia is selected for the TH propulsion concept assessment. Needless to say, the thruster must be fully assessed and requalified for specific duty cycles and operating conditions of actual applications

As previously stated in Table 4.1 when compared to the pressure-regulated system, the blowdown mode would consume more propellant, to compensate for the engine performance loss due to its less-efficient operation over a wide range of inlet pressures. Typically, engine efficiency is directly proportional to the inlet pressure. Figure 6.4 shows the Isp curse as a function of P_{in}. The Isp curve in blue is obtained from test data provided in Ref. 18 for the R-4D nozzle/throat area ratio of 164:1. The curve in orange is scaled for the ratio 44:1 since the TH RCS thruster will have a smaller exit area ratio. The Isp for the orange curve is then used to estimate the propellant consumption for the blowdown mode.



Ref. 1: R-4D with nozzle exit to throat area ratio of 164:1,
$y=270.32+0.37x-1.12e^{-3}x^2+1.12e^{-6}x^3$, AIAA93-2517, Fig. 3-12

Figure 6.4: Scaling of R-4D Isp for Blowdown Mode Operation

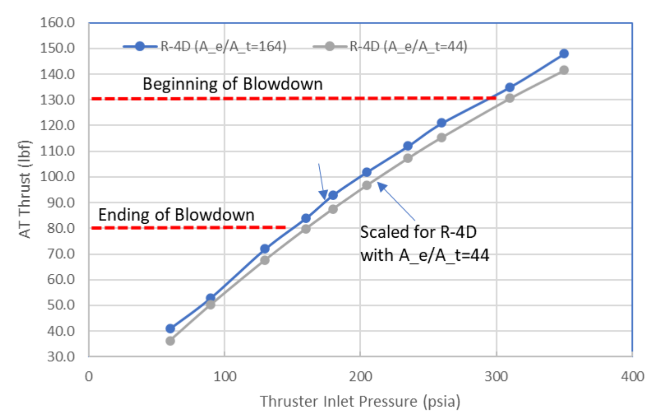
Isp varies from ~300 sec with P_{in} of 310 psia down to 295 sec with P_{in} of 170 psia. It should be noted that these Isp values are for steady-state operation of the engine. When the engine is pulsed, Isp would be lower, relative to the impulse bit (or electrical on-time) of the pulse. For the sake of conservatism, a margin of 3% in Isp is included on the lower end. This leads to Isp of 289 sec which is used to estimate the propellant consumption. It should be noted that the average Isp on the operation pressure range would be 297 sec. Hence, using Isp of 289 sec for the entire blowdown operation would be conservative. The propellant mass breakdown per mission phase for the pressure-regulated shown in Table 2.1 is then updated for the blowdown using Isp of 289 sec. The results are shown in Table 6.1. The propellant refill would be approximately 734 kg. By adding some margin and reserve, the propellant to be refilled would be 819kg [734kg plus 11kg for margin and 10% reserve] for the blowdown, instead of 781kg as estimated for the pressure regulated system. The propellant tank is sized with inclusion of propellant residuals of 15%, reserve of 10%, and mixture ratio bias error of 1%. The propellant consumption for an entire mission would increase by 165kg [from 4362kg for the pressure-regulated to 4527kg for the blowdown].

Table 6.1: Propellant Load Design Point and Refueling for Blowdown Operation

Event #	TH Burn Event	Delta_V [m/s]	Metallic Side Propellant Burned [kg]	Inflatable Side Propellant Burned [kg]	Total Prop Burned [kg]	Metallic Side Propellant Total [kg]	Inflatable Side Propellant Total[kg]
1	Null tip off rates after launch	1	6.03	6.03	12.06	594.54	733.97
2	Maintain attitude in MEO while waiting for boost stage	3	18.09	18.09	36.17		
3	Passive docking with boost stage	5	30.09	30.09	60.19		
17	Active docking with Gateway	45	268.62	268.62	537.24		
21a	Gateway stack control Year 1-3	7.5	271.71		271.71		
21b	Gateway stack control Year 4-6	7.5	271.71		271.71	271.71	
21c	Gateway stack control Year 7-9	7.5	271.71		271.71	682.85	
23	Active undocking with Gateway	45	411.14	411.14	822.28		
24	Active docking with Mars Transit Vehicle	45	404.90	404.90	809.81	733.08	733.08
34	Active undocking with Mars Transit Vehicle	45	328.18	328.18	656.36		
35	Active re-docking with Gateway	45	323.20	323.20	646.39	323.20	323.20
	Usable propellant		2197.81	2197.81	4395.63		
	Propellant residual (3%)		65.9343915	65.9343915	131.868783		
	Total Propellant Required		2263.747442	2263.747442	4527.49488		
	Refuel 1: Refuel Metallic Side at Gateway						
	Refuel 2: Refuel Metallic Side at Gateway						
	Refuel 3: Refuel Metallic & Inflatable Sides in Transit from Gateway to Mars Transit Vehicle						
	Refuel 4: Refuel Metallic & Inflatable Sides in Transit from Gateway to Mars Transit Vehicle						

6.3 Thrust and MIB of RCS Thruster Operating with Blowdown Mode

The thrust and MIB of an RCS thruster vary throughout the blowdown operation. As described in Section 5.11.3, their ranges must be acceptable to GNC. Figure 6.5 shows R-4D thrust vs. P_{in}. The thrust for an exit area ratio of 44 varies from 130 lbf at P_{in}=310 psia down to 80 lbf at P_{in}=170 psia. Subsequently, the bounding MIB, associated with maximum thrust (130 lbf) and minimum electrical pulse width (30 msec) would be 4.4 lbf-sec. Both the thrust range and MIB are acceptable to GNC (see Attachment B).



Ref. 1: R-4D with nozzle exit to throat area ratio of 164:1, $y=9.5344+0.5386x-5e^{-3}x^2+2e^{-6}x^3$, AIAA93-2517, Fig. 3-1

Figure 6.5: R-4D Thrust vs. Inlet Pressure

6.4 MEL of Forward and Aft Propulsion with Blowdown Concept

The MEL of the TH propulsion system with the blowdown concept is shown in Appendix C. The list is similar to the one for the pressure-regulated system (see Appendix B), except for the removal of the helium pressurization, helium refilling, and ullage venting assemblies. The burst disk and pressure relief valves for the propellant tanks are no longer needed for the blowdown. The propellant tanks and their supporting structure are heavier than the pressure regulated. The rest of the component unit mass would be the same as seen on the MEL of the pressure regulated.

6.4.1 Estimate of Propellant Tank Size and Dry mass for Blowdown Concept

Heavy propellant tanks would be a significant drawback for the blowdown propulsion concept. The tanks used for blowdown must be larger than for pressure-regulated, due to the blowdown tanks being required to contain all pressurant within the blowdown tanks and additional propellants to compensate for the overall decrease in engine efficiency during the mission. The tank must also handle higher pressures. Assuming a pressure drop between the tank and thruster of roughly 40 psia, the initial tank pressure would be 350 psia when P_{in} at 310 psia. The final tank pressure would be 210 psia for the P_{in} at 170 psia prior to the refueling. This high initial pressure (350 psia) and additional propellant are then used to figure out the tank size and mass. It is noticed that the pressure of the pressure-regulated tank is 250 psia.

Figure 6.6 shows the sizing of the propellant tank for the blowdown system, using the ACO propulsion tool. Since the fuel tank is slightly larger than the oxidizer, the fuel tank size will be used for both propellants. Because the helium will be stored within the propellant tank, the initial tank ullage would be 60% of the tank volume, instead of 3% as seen for the pressure regulated system. This initial ullage amount would ensure the final tank pressure of 210 psia. The tank volume for the blowdown tank is approximately 2.3 times larger than for the pressure-regulated tank.

Tank Sizing Calculation				Oxidizer Ullage Percentage	60.00%
				Fuel Ullage Percentage	60.00%
Oxidizer			**Fuel**		
Ox. Operating Pressure	1.72E+06	Pa	Fuel Operating Pressure	2.41E+06	Pa
Factor of Safety	1.4		Factor of Safety	1.4	
Oxidizer Volume	0.40	m^3	Fuel Volume	0.405	m^3
Number of Oxidizer Tanks	4		Number of Fuel Tanks	4	
Total Volume	1.00	m3	Total Volume	1.011	m3
Ullage Volume	0.60	m3	Ullage Volume	0.6068	m3
Total Volume	**1.0028**	**m3**	**Total Volume**	**1.0114**	**m3**
			Spherical Tanks		
Oxidizer			**Fuel**		
Spherical Radius	0.391	meters	Spherical Radius	0.3923	meters

Figure 6.6: Propellant Tank Sizing for Blowdown Propulsion Concept

Using the common PVW method to scale the tank mass from SS RCS propellant tank data, the tank mass for the blowdown would be approximately 23.8 kg, instead of 6.9 kg for the tank in the pressure regulated system. The parameters used for the scaling and the results are shown on Table 6.2.

Table 6.2: Propellant Tank Mass Scaled from SS RCS Tank

Parameters	SS RCS Tank	TH tank Pressure-Regulated	TH tanks Blowdown
Inside Tank Diameter (m)	0.99	0.58	0.78
Tank Pressure (psia)	243	250	350
Tank Mass (kg)	32.8	6.9	23.8

6.4.2 Propulsion Mass Comparison between Blowdown and Pressure-Regulated

Detailed breakdown comparisons of key operating parameters, propellant consumptions, tank parameters, and propulsion dry mass, are presented in Table 6.3. The table shows the comparisons for the forward and aft propulsion systems. A key operating parameter describing the differences between the two concepts is the blowdown ratio, which is the ratio between the initial and final tank pressures. Selection of the ratio is driven by the thruster performance, operating capabilities, and the acceptable thrust range. For the R-4D thruster, the blowdown ratio would be 1.76 [350 psia/210 psia]. The tank pressure for the pressure-regulated concept would be the same throughout the operation. Because the thrusters do not operate at an optimum inlet pressure at all times, the blowdown would require roughly 88kg [combined forward and aft propulsion systems] more propellants between refills.

As described in previous sections, the blowdown does not require a helium pressurization, helium refilling, and ullage venting assemblies; however, its propellant tank mass is significantly heavier than for the pressure-regulated system. Additionally, the tank supporting structure for the blowdown system must be also stronger to handle the heavier tanks. The supporting structure mass is partly book-kept under Propellant Management and Distribution System items. Subsequently, the combined dry mass of the forward and aft propulsion system on the blowdown is 195 kg heavier than for the pressure regulated system. Overall, the propulsion wet mass of the blowdown is 278 kg heavier than the pressure regulated system.

Table 6.3: Detailed Breakdown Comparisons of Blowdown and Pressure Regulated

Parameters	Forward (Metallic Side) [*]		Aft (Inflatable Side) [*]	
	Blowdown	**Pressure Regulated**	**Blowdown**	**Pressure Regulated**
Key Operation Parameters				
Isp (sec)	289	300	289	300
Mixture ratio	1.65	1.65	1.65	1.65
Initial Propellant Tank Pressure (psia)	350	250	350	250
Final Propellant Tank Pressure (psia)	210	250	210	250
Blowdown Ratio	1.67	N/A	1.67	N/A
Propellants Mass - Total (kg)	**934.06**	**890.17**	**934.06**	**890.17**
Useable Propellant Mass (kg)	745.00	710.00	745.00	710.00
Residual Propellent (%)	15%	15%	15%	15%
Reserve Propellant (%)	10%	10%	10%	10%
Fuel Bias Mix Ratio Error (%)	1%	1%	1%	1%
Oxidizer - Total (kg)	579.83	552.59	579.83	552.59
Fuel - Total (kg)	354.23	337.58	354.23	337.58
Pressurant Mass - Total (kg)	**2.37**	**3.17**	**2.37**	**3.17**
Propellant Tank Data				
Tank Diameter (m)	0.788	0.583	0.788	0.583
Initial Tank Ullage (%)	60%	3%	60%	3%
Number of fuel tanks	4	4	4	4
Number of oxidizer tanks	4	4	4	4
Propellant Tank Dry Mass (kg)	23.80	6.91	23.80	6.91
Pressurant Tank Data				
Number of Pressurant tanks	0	2	0	2
Pressurant Tank Dry Mass (kg)	N/A	7.06	N/A	7.06
Propulsion System Dry Mass [*] (kg)	**668.25**	**570.72**	**594.95**	**500.14**
Ullage Venting Assembly (kg)	N/A	36.58	N/A	36.58
Helium Pressurization Acquisition & Storage (kg)	N/A	18.32	N/A	18.32
Helium MGMT & Distribution System (kg)	N/A	41.55	N/A	41.55
Helium Resupply Equipment (kg)	N/A	32.73	N/A	32.73
Thruster Generation Equipment (kg)	96.60	96.60	57.96	57.96
Propellant MGMT & Distribution System (kg)	174.06	98.41	165.21	89.56
Propellant Acquisition & Storage (kg)	227.00	90.68	227.00	90.68
Propellant Resupply Equipment (kg)	81.40	71.03	81.40	73.75
Mounting/install Hardware (kg)	89.19	84.82	63.38	59.01
Propulsion System Wet Mass (kg)	**1604.68**	**1464.06**	**1531.38**	**1393.48**
[*] Mass Growth Allowance (MGA) is included in the mass estimate				
Highlight		**Difference**		**Difference**
Dry Mass of Blowdown (kg)	668.25	97.53	594.95	94.81
Dry Mass of Pressure Regulated (kg)	570.72		500.14	
Propellants for Blowdown (kg)	934.06	43.89	934.06	43.89
Propellants for Pressure Regulated (kg)	890.17		890.17	
Helium Pressurant for Blowdown (kg)	2.37	-0.80	2.37	-0.80
Helium Pressurant for Pressure Regulated (kg)	3.17		3.17	
Blowdown heavier than Prop Reg. (kg)	140.62		137.90	
Blowdown heavier than Prop Reg. in Total (kg)	***278.51***			

Table 6.4 illustrates the mass comparison in terms of percentage, referenced to the pressure-regulated system at 100%. Removal of the helium pressurization, helium refilling, and ullage venting for the blowdown would reduce the mass by 9%. However, the mass-saving is nullified out by the propellant tank mass increase of 9%. The tank supporting structure under Other Assemblies and Secondary Structure item accounts for the heavier mass. Subsequently, the dry mass of the blowdown system is 7% higher than the pressure regulated system. The propellants and helium account for a 3% increase. Ultimately, the wet mass of the blowdown system is 10% higher than the pressure-regulated system.

Table 6.4: Mass Comparison between Blowdown and Pressure-Regulated Systems

Major Breakdown Mass	Blowdown	Pressure Regulated
System Dry mass	**44%**	**37%**
Propellant tanks	13%	4%
Propellant Resupply Assemblies	6%	5%
Ullage Venting Assemblies	0%	3%

Pressurization Assemblies	0%	4%
Pressurant Resupply Assemblies	0%	2%
Other Assemblies & 2nd Structure	25%	19%
Propellants & Helium	**66%**	**63%**
Total Percentage	**110%**	**100%**

7 Propulsion Technology Advancements for TH Propulsion

The selection of the propulsion concept and architecture for the TH is primarily driven by the requirement of multiple propellant refilling capability and reliable operation for an entire 15-year mission. Enabling propulsion technology must be conducted to raise the TRL for the human-rated system. A rough outline of the technology advancement paths can be depicted through a decision tree shown in Figure 7.1. Depending on the selected propulsion concept paths for TH, some key propulsion technology advancements are required.

For a propulsion system being refueled, the technology level of the FTC used in transferring fluids from supply vehicle to TH must be examined.

As described in the previous section, although the propellants used by the Russian propulsion module on the ISS have been resupplied, such a technology must be improved for the TH mission. The design development test and evaluation of an umbilical with transfer couplings involving both propellant and high-pressure helium is not a trivial activity. There were a lot of subtle and not so subtle design challenges associated with umbilical loading under the different pressure conditions on the Shuttle Orbiter/ET umbilical, for examples, where the different loads caused different deflections and potential for leakages. This complex interface should not be underplayed.

The blowdown propulsion system has the helium pressurant stored in the same tanks as the propellant. The tank pressure is reduced as the propellant is consumed. The pressurant in the tanks is then recompressed to a higher tank pressure when refilling the liquid propellants. Since a PMD is utilized, minor issues (e.g., gas being trapped within PMD during the refill) need to be addressed for the TH application. Otherwise, no major enabling technology advancement is identified for the blowdown concept.

In contrast to the blowdown system, a pressure-regulated system would require venting the propellant ullage while refilling. The type of propellant tank selected for the system would drive the technology needs. For positive expulsion tanks, which have a physical barrier between the pressurant and propellants, there are mission life and cycle life issues which would require technology maturation. As described in the propellant tank assessment/comparison shown on Table 4.2, a liquid/gas membrane, whether it be metal diaphragm or polymeric, would be required. However, they are currently not intended for the reuse (in the case of metal diaphragm) nor compatible (in the case for polymeric) with propellants for long duration exposure. Technology maturation of these positive-expulsion membranes would be required to enable the use of positive-expulsion tanks for the TH mission.

When PMD tanks (nonpositive expulsion tanks) are utilized, there is a need for a device that would allow the preferential venting of ullage gas from the propellant tank, while retaining the liquid propellant inside the tank. A past program [19] proposed a combination of complex tank arrangements and propellant settling burns while venting. However, this method would be very challenging for TH operation. There have been some efforts to develop the technology for liquid gas phase separation devices. This study has baselined a gas port phase separator device [14, 15]. Such devices could be used to prevent liquid propellant leaving the tank while venting. However, this gas port phase separator device is currently designed for use in cryogenic tanks, supporting a cold-gas RCS, and would likely require a technology development effort for the device to be applicable to NTO, MMH, and helium for the TH mission.

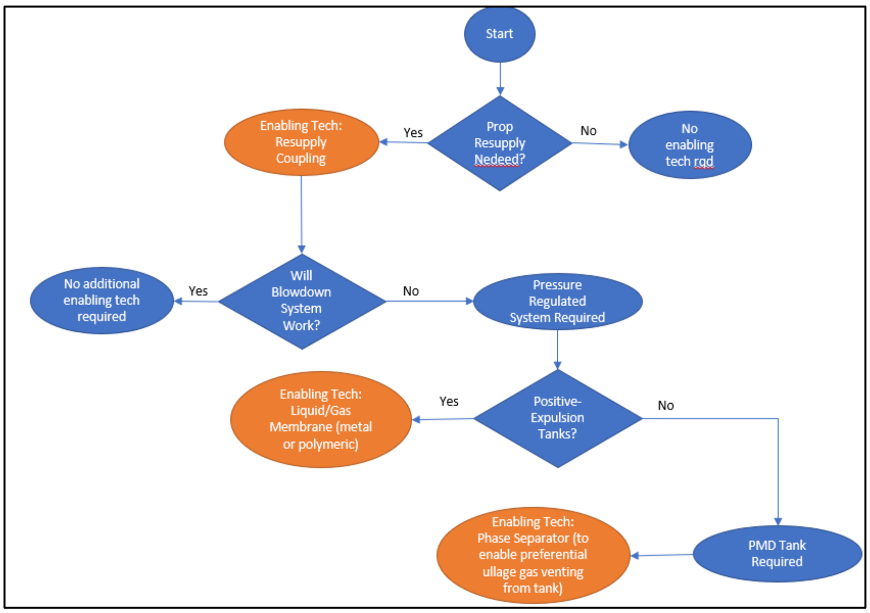


Figure 7.1: Decision Tree of Technology Advancement for TH Propulsion System

8 Pros & Cons of the Blowdown concept

Pros and cons of the blowdown concept are presented on Table 8.1. In comparison with the pressure-regulated system, the blowdown system would have a smaller number of components, which could benefit other subsystems – e.g., avionics, thermal, power, and structure. Additionally, mass reductions in valve drivers and instrumentation can be realized. There is no need for insulation and heater power for these components. These benefits can be keys factors for selecting the blowdown concept as the TH propulsion system baseline. The downside of the blowdown system is that it heavier than the pressure-regulated system. Its heavy tanks need additional structural support. There will be variation in thrust throughout the mission, which must be acceptable to GNC.

Table 8.1: Pros and Cons of Blowdown Propulsion Concept

PROS	
Higher reliability in operation and	• Blowdown system has a smaller number of components than

system failure modes than a pressure regulated system	the pressure-regulated due to no assemblies for helium pressurization, helium refilling, and ullage venting, and tank pressure relief. Hence, the blowdown system has less failure modes. It is important for a 15-year mission of active usage of all components, from a reliability perspective. For a 1-FT architecture, after the first failure, the mission is likely over and the focus is on returning the crew home safely (if already on board), or not sending crew if not there already. • For nominal operating conditions, the highest pressure in system is the propellant tank pressure of ~350 psia, while the pressure regulated systems have helium pressures of ~4000 psia. Higher pressure would result in higher risk of failure modes (leakage, propellant tank over pressurization, etc.) and more operating challenges (e.g., helium control valve failure). • Helium pressurization components in the pressure regulated systems may not be fully compatible per material perspectives. There are concerns of propellant vapor migration and mixing in the pressurization system. On the other hand, the blowdown system is free of these concerns.
Less impacts on other sub-systems within TH element	• Blowdown systems have less instrumentation, fewer valve drivers, and fewer harnesses. The system is less demanding on Avionics in comparison with the pressure regulated system. • Blowdown systems are less demanding on power for heater and valve operation than pressure regulated systems. • Blowdown system would not require as much as thermal conditioning and protection, such as insulation and heater strips seen on pressure regulated systems. • Less demand on other sub-systems would lead to mass reductions which are not considered in the propulsion MEL.
Possible simplicity in propellant tank design	• No helium flows into blowdown propellant tanks, as can happen with the pressure regulated systems. Although the current tank mass estimate is based on SS RCS tank, PMDs for the blowdown system may be much simpler (e.g., using sponge tank for a whole tank rather than complex screen gallery). This design may lead to tank mass reduction. • Blowdown systems do not need burst disk and pressure relief since there is no high-pressure.
Simplified on propellant refilling	• Blowdown systems do not vent tank ullage gas. Subsequently, there are no concerns of propellant contamination on external surfaces and/or external components of TH. • No refilling helium is theoretically needed. Resupply operations are much simpler since it is not high-pressure helium transfer. Over course of the long mission, there may be a small loss of helium. Helium can be transferred through the normal propellant refilling (e.g., helium entrainment, oversaturation).

Less advancing /enhancing technology needed	• Some enhancement of PMDs is needed to avoid ullage gas trapped in the system during tank refilling. • Possible minor changes and/or requalification of the thruster. • Less system development schedule risk • See section 7 on enabling technology for details
CONS	
Thrust varies throughout the operations	• Blowdown systems have high thrust at the beginning of the blowdown and lower thrust at the end. That creates some complexities for GNC. The variations in thrust and MIB must be within acceptable ranges for GNC. • Thruster performance (e.g., thrust, efficiency) decreases as the tank pressure decreases during the operation. Subsequentially, additional propellant is needed to compensate for the performance loss.
Large propellant tank volume	• Propellant tank volume for the blowdown system must be larger than for pressure regulated systems. The tanks would require more volume to account for larger initial ullage gas and more propellant needed, although helium tanks are not needed.
Heavy propulsion system wet mass	• Blowdown propulsion system wet mass is greater than for pressure regulated systems. However, the masses of sub-systems involving the propulsion operations (e.g., avionics, thermal, and power) are smaller. That could lead to a marginal increase on TH element.
Potential issues on thruster operation	• The chamber wall and throat have higher heating at higher engine inlet pressure. Chamber coating life would be reduced due to high wall temperatures. There could be a potential of having keep-out zones on engine duty cycle to avoid overheating. • There is a potential for engine chug instability at low engine inlet pressure. • Mixture ratio shift caused by tank temperature fluctuation and/or variation between fuel and oxidizer would lead to mixture ratio shift. Oxidizer tank pressure shift due to the oxidizer high vapor pressure. The shift would impact engine performance (e.g., Isp) and life (e.g., high wall temperature). • Additional engine qualification, operating constraints, and possible hardware changes may be needed to address the issues.

9 Summary and Conclusion

Considerable efforts have been dedicated to examining a pressure-regulated system for TH application. A technical peer review was performed with participation of experts in spacecraft propulsion system design and components at MSFC. The team provided valuable inputs on the flow schematic design and propulsion component selection suitable of meeting TH RCS propulsion system requirements. It should be noted that many TH requirements do not exist, and the Propulsion Team had to make some assumptions for requirements that could drive system design.

To satisfy 1-FT tolerance for function and 2-FT tolerance against catastrophic events, component redundancy is incorporated in the propulsion concept design. Instrumentation laid out in the schematic would be used to gather data, to monitor the health of the propulsion system and to support quantity gauging of the propulsion system fluids.

For the pressure-regulated concept, venting the ullage gas in the propellant tank overboard is a selected method for decreasing tank pressure prior to liquid propellant refill. This operation, however, would pose a significant concern to the external surfaces of the TH. A liquid/gas separator would be required to eliminate, or at least significantly reduce, the amount of liquid propellant expelled in the vented gas mixture. The TRL of the phase separator for the TH must be further advanced. Metal diaphragm and non-positive-expulsion PMD propellant tank systems were traded against each other, with the PMD architecture being selected.

A blowdown concept was also evaluated. Its flow schematic was derived from the pressure-regulated concept, with removal of assemblies involving the helium pressurization and ullage venting. Although its system wet mass is 10% heavier than the pressure-regulated system due to larger propellant tanks and more propellants needed, the blowdown concept offers simplified and reliable operations and benefits to other TH subsystems. The blowdown concept is selected as a current baseline for the TH RCS propulsion.

The report also highlighted key trade studies and design decisions, including pros and cons of the selected concept. Technology advancements of propulsion components are also identified. Other appropriate options, relative to components for consideration, are also pointed out for future assessments.

Acknowledgments

The authors wish to thank Christopher Popp, Brad Addona, Jack Chapman, Scott Kramer, and Jonathan Bentley for their participation in the peer review. Technical inputs on the flow schematic, component selection from the entire review team were greatly appreciated. Brad Addona also provided component data for developing the propulsion MEL. Scott Kramer contributed information on the propellant tank data. Christopher Popp and Daniel Dorney devoted their time on commenting and editing this report. The authors would like to recognize Andrew Choate for his programmatic and managerial support for this work. Jim Meehan and James Owens provided valuable inputs on the propulsion conceptual design, regarding engineering and structural integration to the TH element. Quincy Bean supported on the tank sizing and mass estimate. He gave guidance on the use of ACO Propulsion Tool. Victor Tapia provided feedback on thruster performance and operations per GNC perspectives.

Reference

1. K. Goodliff, D. Craig. "HEOMD Strategic Campaign Operations Plan for Exploration," September 28, 2021. https://ntrs.nasa.gov/citations/20210022080
2. Choate, J. A., et al., "NASA's Moon to Mars (M2M) Transit Habitat (TH) Refinement Point of Departure (PoD) Design," IEEE International Conference on Communications 28 May – 01 June 2023, Rome, Italy
3. Harris, W. Danny, et al., "Moon to Mars (M2M) Habitation Considerations A Snapshot as of January 2022" NASA/TM-20220000524
4. Quincy Bean, "Propellant Load & Refueling Cadence," Presentation, Sept. 2022
5. https://space.stackexchange.com/questions/60707/how-do-propellant-transfer-technologies-work#comment201938_60707
6. Sanders, B. Gerald, et al., "Russian Propulsion & Propellant Resupply Systems for the ISS" – JSC-27979 Rev. F
7. Pierce, W. Charles, et al., "A Review of In-Space Propellant Transfer Capabilities and Challenges for Missions Involving Propellant Resupply" – NESC-TI-01293 CD (NRB 4-16-20).
8. https://www.nasa.gov/centers-and-facilities/goddard/nasa-satellite-servicing-technologies-licensed-by-northrop-grumman/
9. Rotenberger, S., et al., "Orbital Express Fluid Transfer Demonstration System," 08-03297 JANNAF.
10. https://www.medicaldesignandoutsourcing.com/what-is-nitinol-and-where-is-it-used/
11. Trinh, H., "Peer Review Transit Habitat Propulsion System (Metallic Side) Flow Schematic Update," Presentation charts, December 26, 2023.
12. Bemis R., Murphy J.M., "Space Shuttle – Reaction Control System Tanks"
13. ANSI/AIAA S-120A-2015 (R 2019), Mass Properties Control for Space Systems.
14. Behruzi, Philipp, Passive Phase Separation in Cryogenic Upper Stage Tanks, AIAA 2013-3905, 49th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, July 14-17, 2013, San Jose, CA.
15. Behruzi, Phillipp, et al., Liquid-gas phase separation technologies for ballistic flight phases, AIAA Propulsion and Energy Forum, 10-12 July 2017, Atlanta GA, 53rd AIAA/SAE/ASEE Joint Propulsion Conference.
16. ACO Propulsion Tool (Version 7)
17. Aerojet 2006-H-3301 data Sheet, R-4D 490N (110-lbf) Bipropellant Rocket Engine
18. Ellison, J.R., et al., Extended Pressure Range Performance of the Kaiser-Marquardt 490N Thruster, AIAA-93-2517, AIAA/SAE/ASME/ASEE 29th Joint Propulsion Conference and Exhibit, June 28-30, 1993 / Monterey, CA
19. Robert Stout, "International Space Station Propulsion Module Propulsion System Instrumentation Report," PM DPDR-0080, March 2000.

Attachment A: Technical Exchange on FTC Mass Estimate

Trinh, Huu P. (MSFC-ER11)

From:	Christianson, Rollin C. (JSC-EP4)[Jacobs Technology, Inc.]
Sent:	Friday, December 22, 2023 12:03 PM
To:	Trinh, Huu P. (MSFC-ER11)
Cc:	Nufer, Brian M. (KSC-NEL50); Durning, Joe (JSC-EP411)
Subject:	RE: Estimate half transfer coupler

Huu,

There are several important variables to consider when designing a new bipropellant refueling system, and your table in the email below is a good start. One issue that should be addressed soon is whether or not you intend the refueling fluid coupler to also have its own dedicated mechanical latching / locking device. If you are able to leverage the same locking device used to keep the vehicles mated, that could reduce your overall mass considerably.

I am not at liberty to disclose proprietary info regarding other refueling docking couplings, but it seems reasonable that each half of the fluid coupler could be around 15 Lbm or less, depending upon preferred design features. If you have additional thoughts, we might be able to fine-tune the estimate.

Thanks,

Rollin

Rollin Christianson | Oceaneering | Jacobs JETS Contract | Sr. Propulsion Systems & Integration Engineer
O: +01.281.483.0455 | M: +01.414.614.7341 | rollin.c.christianson@nasa.gov
2101 E. NASA Pkwy Bldg 15 / Room 162 | Houston, TX 77058 USA

From: Trinh, Huu P. (MSFC-ER11) <huu.p.trinh@nasa.gov>
Sent: Friday, December 22, 2023 11:12 AM
To: Christianson, Rollin C. (JSC-EP4)[Jacobs Technology, Inc.] <rollin.c.christianson@nasa.gov>
Cc: Nufer, Brian M. (KSC-NEL50) <brian.nufer@nasa.gov>
Subject: RE: Estimate half transfer coupler

Hi Rollin,
Thanks for your response. For now, I'm asked to update the MEL of Transit Habitat RCS propulsion system. We have a requirement of refilling propellants (MMH and NTO) and helium on Transit Habitat. I think the Gateway also has a similar requirement of refuel. At any rate, I have no idea on a ballpark mass of a half fluid transfer coupler on the receiving spacecraft. Just want to get an rough mass estimate for the unit.
I don't think the project is looking more details of the design at this time.
Huu

Attachment B: Technical Exchange with GNC on Thruster Operations

[1/25 4:17 PM] Trinh, Huu P. (MSFC-ER11)

No minimum number of thruster operating at one time. Again, maximum of thrusters operating at one time is 8.

[1/25 4:25 PM] Tapia, Victor Joel Cabezas (MSFC-EV41)

Minimum on-time is the smallest firing duration a thruster can achieve. Thruster valve and manifold pressure impact the minimum on-time which can effect if a spacecraft can achieve effective and precise control.

[1/25 4:27 PM] Tapia, Victor Joel Cabezas (MSFC-EV41)

Not sure how to quantify the impact of the pressure drop on the on-time, but was wondering if it was something you already considered.

[1/25 4:28 PM] Tapia, Victor Joel Cabezas (MSFC-EV41)

Thank you and excellent presentation and delivery! Thank you for taking the time to walk me through it.

[1/25 4:28 PM] Trinh, Huu P. (MSFC-ER11)

- Total Impulse Demonstrated
  .... 20,016,000 N-sec (4,500,000 lbf-sec)
- Total Pulses 20,781
- Minimum Impulse Bit .... 15.6 N-sec (3.5 lbf-sec)
- Demonstrated Steady State Firing .... 12,000 sec

[1/25 4:30 PM] Trinh, Huu P. (MSFC-ER11)

What is your minimum impulse bit requirement?

[1/25 4:32 PM] Trinh, Huu P. (MSFC-ER11)

My guess is that the mim impulse bit would be higher than 15.6N when the thruster operates with 130-lbf, while the mim. impulse bit would be less than 15.6N.

[1/25 4:39 PM] Tapia, Victor Joel Cabezas (MSFC-EV41)

Not a shall, but I'm currently tracking 32ms for this 130lbf thruster. For the decrease to 80 lbf I'll estimate 50ms based on these values.

[1/25 4:44 PM] Trinh, Huu P. (MSFC-ER11)

Good points. Let me check on the valve timing and get back with you. When you come up the on-time, do you base on a constant thrust? I think there is a thrust curve.

[1/25 4:46 PM] Trinh, Huu P. (MSFC-ER11)

I will get back with you on the thruster curve.

[2/2 12:56 PM] Trinh, Huu P. (MSFC-ER11)

Hi Victor, I have ditched into R-4D thruster report, TMC Report A-1075. It appears that R-4D was capable to operate even smaller pulse width (~10 msec, 20 msec). I choose data of 20 msec pulse width and scale to engine inlet pressure of 310 psia (equivalent to 130 lbf as you stated), the impulse bit for this case would be around 2.92 lbf-sec. I think it would be satisfactory to GNC. Is it correct?

[2/7 9:19 AM] Tapia, Victor Joel Cabezas (MSFC-EV41)

Good morning Huu, Could you send me the R-4D report you reviewed? I have seen mentions of minimum on time as low as 30-40 ms during design as an optimistic value, but after rigorous testing and analysis on the hardware the value converged closer to 100ms to ensure reliability and functionality for a desired thrust magnitude.

[2/7 9:26 AM] Trinh, Huu P. (MSFC-ER11)

Hi Victor, I'm going to send you the link to the report. Here are some highlights.

[2/7 9:26 AM] Trinh, Huu P. (MSFC-ER11)

Each configuration was first tested to determine the inlet pressures which were necessary to achieve a mixture ratio (O/F) of 2.03 ± 0.03 and a chamber pressure of 96.5 ± 2.5 psia using 75 ± 10°F propellants. These flowing inlet pressures were then used for all subsequent tests on that configuration. Each configuration was subjected to the following basic test matrix or portions of it, at four different propellant and engine temperature conditions.

Item No.	Electrical "ON" Time	Electrical "OFF" Time	Number of Pulses	Number of Runs
1	10 ± 1 ms	490 ± 5 ms	300 $^{+2}_{-0}$	1
2	20 ± 2 ms	480 ± 5 ms	150 $^{+2}_{-0}$	1
3	50 ± 2 ms	450 ± 5 ms	60 $^{+2}_{-0}$	1
4	100 ± 2 ms	100 ± 5 ms	30 $^{+2}_{-0}$	1
5	5 ± 0.5 sec.	-	1	3
6	100 $^{+5}_{-0}$ sec.	-	1	1

The temperature conditions used were:

(i) propellant temperatures = 75 ± 5°F
injector head temperature = 50°F to 125°F

(ii) propellant temperatures = 40 ± 5°F
injector head temperature = 50 ± 5°F

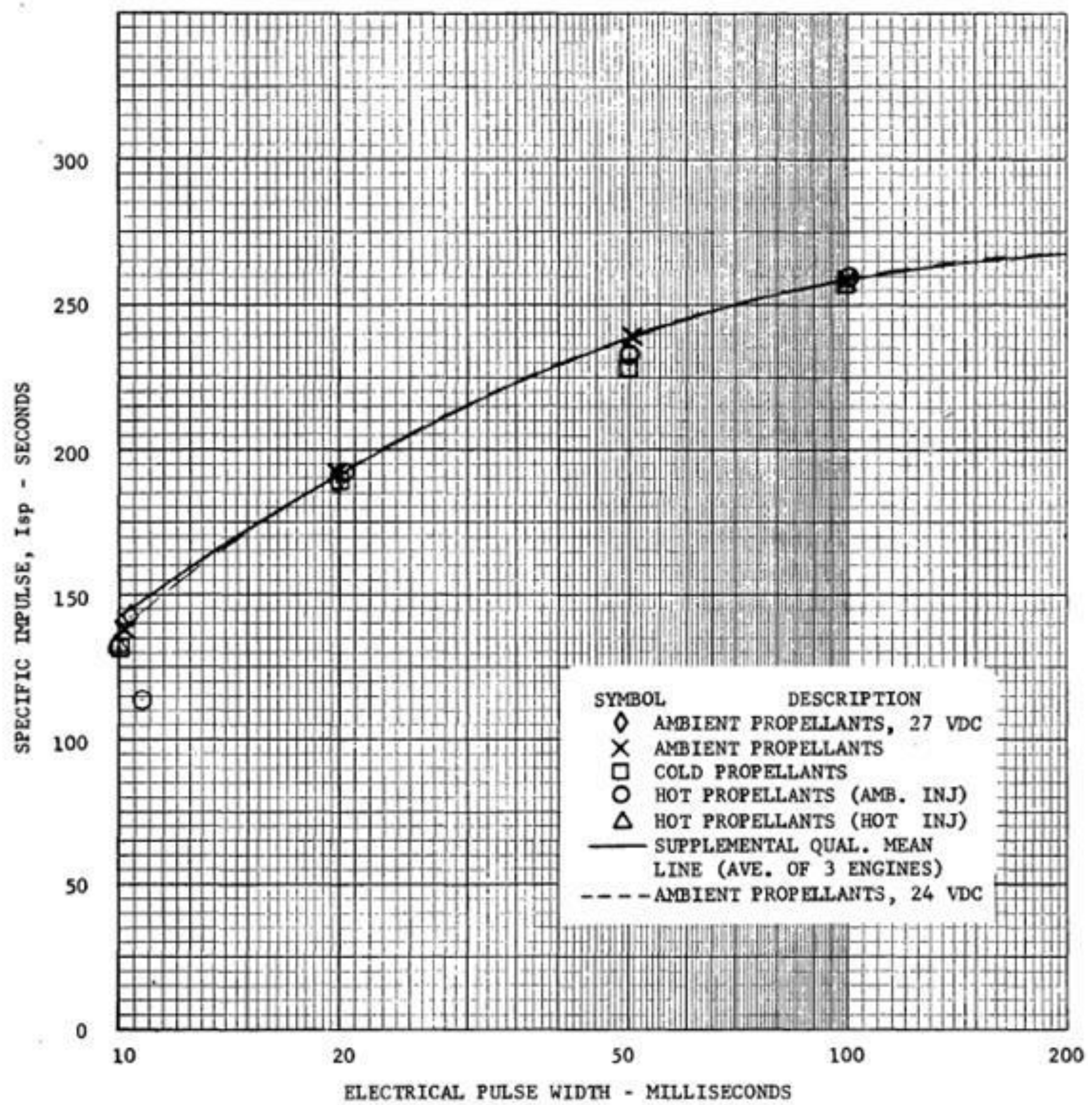
(iii) propellant temperatures = 100 ± 5°F
injector head temperature = 50°F to 125°F

(iv) propellant temperature = 100 ± 5°F
injector head temperature = 250 ± 10°F

[2/7 9:28 AM] Trinh, Huu P. (MSFC-ER11)

SPECIFIC IMPULSE vs. ELECTRICAL PULSE WIDTH

ENGINE P/N X24194-1, S/N 0001
100% CHAMBER COOLING
100% PREIGNITER COOLING
OXIDIZER - GREEN N_2O_4, FUEL - MMH



39

Figure 18

[2/7 9:31 AM] Trinh, Huu P. (MSFC-ER11)

I will plan to assess if there was any issue of the thruster on the actual operation at these small pulse widths.

like 1

[2/7 9:35 AM] Trinh, Huu P. (MSFC-ER11)

Here is the link to the report.

[2/7 9:35 AM] Trinh, Huu P. (MSFC-ER11)

https://moon2mars.ndc.nasa.gov/nextstep/tms/phase3/Extensibility/Transit_Hab/Trades%20and%20Assessments/Propulsion%20System/Propulsion%20Reference%20Documents/TMC%20REPORT%20A-1075.pdf

[2/7 10:53 AM] Trinh, Huu P. (MSFC-ER11)

Hi Victor, there has been an issue of high chamber pressure spike when running R-4D at small pulse width. To avoid it the temperature of the engine and propellants should be kept above 70F with a heater, if needed. I think it would be okay to use 30 msec pulse width. so MBIT ~ 4.4 lbf-sec for the max tank pressure of 350 psia (equivalent to 130 lbf). Is it okay?

[2/7 10:54 AM] Trinh, Huu P. (MSFC-ER11)

Here is a report on this issue (page 35)

[2/7 10:55 AM] Trinh, Huu P. (MSFC-ER11)

TMC REPORT A 1083.pdf

[2/7 11:01 AM] Tapia, Victor Joel Cabezas (MSFC-EV41)

That would be great! Thank you for sending the report. That explains why they defined a 20-500ms range for their test plan. 30ms is still on the lower end of this scale. Does that take into account running the thrusters at a pressure drop of 310 -> 165?

If I remember correctly, previously you showed 130lbf for thrust level. I the following an older spec?

[2/7 11:03 AM] Trinh, Huu P. (MSFC-ER11)

[2/7 11:08 AM] Trinh, Huu P. (MSFC-ER11)

So, 130 lbf when the engine inlet pressure at max (310 psia); 80 lbf when the engine inlet pressure at min (165 psia). When I quote MBIT of 4.4 lbf-sec. It is a worst bounding case for GNC perspective. For an nominal/optimum engine conditions, thrust ~ 100 lbf. Does it make senses to you?

[2/7 11:27 AM] Tapia, Victor Joel Cabezas (MSFC-EV41)

That makes sense. I'll use your suggestion of 30 ms min-on-time.

like 1

[2/7 11:27 AM] Tapia, Victor Joel Cabezas (MSFC-EV41)

Thank you!

[2/7 12:41 PM] Trinh, Huu P. (MSFC-ER11)

Just wonder any other concerns/issues for switching to the blowdown propulsion system.

[2/7 12:52 PM] Tapia, Victor Joel Cabezas (MSFC-EV41)

I'll have to update my sim and run a quick analysis to make sure there are no areas of concern. Jim mentioned that there is not a plan to update what is sent to Gateway for the post-IAC10 work. As I get more availability, I will make the changes and let you know how the results look.

[2/7 12:57 PM] Trinh, Huu P. (MSFC-ER11)

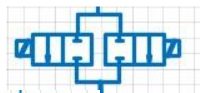
Sound good! we will update the propulsion system w/ the blow down concept when the next opportunity occurs. Just want to make sure if I need to provide you, GNC expert, any information/data. Keep me in the loop.

[2/7 1:00 PM] Tapia, Victor Joel Cabezas (MSFC-EV41)

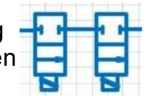
You've given me great feedback. Thank you Huu! Will do.

Familiarizing some basic component arrangement features

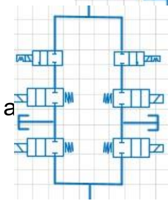
- Redundant valve in parallel for protecting against valve failed-closed



- Redundant valve in series for protecting against valve leak and/or valve failed-open

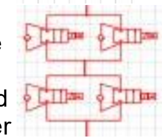


- (1-FT) redundant valve in parallel-series against catastrophic failure due to valve failed-open[1], e.g., helium control valve failing to close at its opening position would lead to propellant tank over-pressurization.

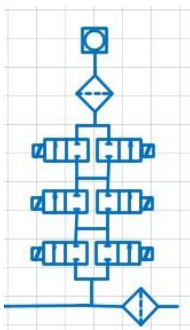


(1) For some instances, either parallel-series or figure-eight configuration can be used to meet an intent of 1-FT. Operational reliability will be performed for down-selecting best-fit valve arrangement.

- (1-FT) redundant valve in figure-eight configuration against failure due to valve failed-closed[1], e.g., propellant iso valve failing to open at its close position would lead to propellant unavailable for thruster operation.



- (2-FT) 3 inhibit barriers for protecting against helium overboard leak



2) Propellant tank ullage venting would have mixture to helium and propellant vapor (e.g., OHV106 – Valve on the oxidizer propellant tant ullage venting line.)

Note:
Only components on oxidizer side are labelled. Labels of components on the fuel side are mirrored from the oxidizer side.

Component Notation

X X X # # #

- **F**: fuel; **H**: Helium; **O**: Oxidizer
- **I**: Isolation Valve; **B**: Iso Valve with Back Pressure Relief; B: Burst Disk (when following with D) **C:** Control; **H:** Helium mixture (2) **P:** Pyro valve; **S**: Service **T**: Test
- **C:** Check Valve; **D**: Burst disk **P:** Port, **V**: Valve
- **Even number:** Valve/component on oxidizer system side
- **Odd number :** Valve/component on Fuel system side
- Valve/component number

X OR # # #

- **F**: fuel; **H**: Helium; **O**: Oxidizer
- Orifice
- **Even number:** Valve/component on oxidizer system side
- **Odd number :** Valve/component on Fuel system side
- Component number

7

Appendix B: Propulsion MEL with Pressure-Regulated Concept

SBS ID	EQUIPMENT GROUP (TIER 2)	UNIQUE COMPONENT/SUB-ASSEMBLY (TIER 3)	Qty	Unit Mass (kg)	Basic Mass (kg)	Applied MGA / Reserves (%)	MGA / Reserves (kg)	MGA / Reserves (%)	Predicted Manuf Empty Mass (kg)
5.1.0	**FORWARD PROPULSION SYS (METALLIC SIDE)**		**501**		**504.96**	**0%**	**65.77**	**13.02%**	**570.73**
5.1.1	**THRUST GENERATION EQUIPMENT**		**20**		**92.00**	**0%**	**4.60**	**5.00%**	**96.60**
5.1.1.1		Thruster (445 N, 110 lbf)	20	4.60	92.00	5%	4.60		96.60
		[ENTER COMPONENT/SUBASSY]	0	0.00	0.00	0%	0.00		0.00
5.1.2	**PROPELLANT MGMT & DISTRIB SYSTEM**		**151**		**86.49**	**0%**	**11.92**	**13.78%**	**98.41**
5.1.2.1		Fill/Drain Valve	8	0.21	1.67	5%	0.08		1.75
5.1.2.2		Pyro Valves	4	0.32	1.28	5%	0.06		1.34
5.1.2.3		Propellant Orifice	2	0.01	0.02	5%	0.00		0.02
5.1.2.4		Latch Valve with Back-Relief	52	0.73	37.74	5%	1.89		39.63
5.1.2.5		Propellant Filter	8	0.30	2.39	5%	0.12		2.51
5.1.2.6		Propellant Test port	10	0.21	2.10	5%	0.11		2.21
5.1.2.7		Propellant Feed Lines	1	34.69	34.69	25%	8.67		43.36
5.1.2.8		Pressure Transducers	66	0.10	6.60	15%	0.99		7.59
5.1.2.9		Temperature Sensors	0	0.00	0.00	15%	0.00		0.00
		[ENTER COMPONENT/SUBASSY]	0	0.00	0.00	0%	0.00		0.00
5.1.3	**PROPELLANT ACQUISITION & STORAGE SYSTEMS**		**72**		**80.64**	**0%**	**10.04**	**12.45%**	**90.68**
5.1.3.1		Fuel (MMH) Tanks	4	6.91	27.64	15%	4.15		31.79
5.1.3.2		Oxidizer (NTO) Tanks	4	6.91	27.64	15%	4.15		31.79
5.1.3.3		Pressure Transducers	24	0.10	2.40	15%	0.36		2.76
5.1.3.4		Temperature Sensors	24	0.10	2.40	15%	0.36		2.76
5.1.19		Combined Burst Disk & Pressure Relief	8	2.27	18.16	5%	0.91		19.07
5.1.20		Test Ports	8	0.30	2.40	5%	0.12		2.52
		[ENTER COMPONENT/SUBASSY]	0	0.00	0.00	0%	0.00		0.00
5.1.4	**PROPELLANT RESUPPLY EQUIPMENT**		**71**		**64.30**	**0%**	**6.73**	**10.47%**	**71.03**
5.1.4.1		Propellant Latch valve	40	0.73	29.20	5.00%	1.46		30.66
5.1.4.2		Propellant Filter	4	0.30	1.20	5.00%	0.06		1.26
5.1.4.3		Propellant Half-Fluid Transfer Coupling	4	6.80	27.20	15.00%	4.08		31.28
5.1.4.4		Propellant Feed Lines	1	3.40	3.40	25.00%	0.85		4.25
5.1.4.5		Test Ports	10	0.21	2.10	5.00%	0.11		2.21
5.1.4.6		Pressure Transducers	12	0.10	1.20	15.00%	0.18		1.38
		[ENTER COMPONENT/SUBASSY]	0	0.00	0.00	0%	0.00		0.00

Appendix B: Propulsion MEL with Pressure-Regulated Concept (continue)

SBS ID	EQUIPMENT GROUP (TIER 2	UNIQUE COMPONENT/SUB-ASSEMBLY (TIER 3)	Qt	Unit Mass (kg	Basic Mass (kg	Applied MGA / Reserves (%)	MGA / Reserves (kg)	MGA / Reserves (%)	Predicted Manuf Empty Mass (kg)
5.1.5	**PRESSURANT MGMT & DISTRIB SYSTEM**		**63**		**36.82**	**0%**	**4.73**	**12.83%**	**41.55**
5.1.5.1		Pressurant Fill/Drain Valve	2	0.12	0.24	5.00%	0.01		0.25
5.1.5.2		Helium Orifice	2	0.01	0.02	5.00%	0.00		0.02
5.1.5.3		Pressurant Latch valve	4	1.13	4.52	5.00%	0.23		4.75
5.1.5.4		Check Valve	16	0.23	3.68	5.00%	0.18		3.86
5.1.5.5		Helium Control Solenoid Valves	8	1.25	10.00	5.00%	0.50		10.50
5.1.5.6		Pressurant Filter	2	0.50	1.00	5.00%	0.05		1.05
5.1.5.7		Pressurant Test port	22	0.12	2.64	5.00%	0.13		2.77
5.1.5.8		Presssurant Feed Lines	1	14.12	14.12	25.00%	3.53		17.65
5.1.5.9		Pressure Transducer, Low Pressure Gas	6	0.10	0.60	15.00%	0.09		0.69
		[ENTER COMPONENT/SUBASSY]	0	0.00	0.00	0%	0.00		0.00
5.1.6	**PRESSURANT ACQUISITION & STORAGE SYSTEMS**		**14**		**15.32**	**0%**	**3.00**	**19.61%**	**18.32**
5.1.6.1		Pressurant Tanks	2	7.06	14.12	20.00%	2.82		16.94
5.1.6.2		Pressure Transducer, High Pressure Gas	6	0.10	0.60	15.00%	0.09		0.69
5.1.6.3		Temperature Sensor	6	0.10	0.60	15.00%	0.09		0.69
		[ENTER COMPONENT/SUBASSY]	0	0.00	0.00	0%	0.00		0.00
5.1.7	**PRESSURANT RESUPPLY EQUIPMENT**		**43**		**27.72**	**0%**	**5.01**	**18.09%**	**32.73**
5.1.7.1		Pressurant Latch valve	12	0.34	4.08	5.00%	0.20		4.29
5.1.7.2		Pressurant Filter	4	0.25	1.00	5.00%	0.05		1.05
5.1.7.3		Pressurant Half-Fluid Transfer Couplers	2	6.80	13.60	25.00%	3.40		17.00
5.1.7.4		Pressurant Feed Lines	1	4.24	4.24	25.00%	1.06		5.30
5.1.7.5		Pressure Transducer, High Pressure Gas	6	0.10	0.60	15.00%	0.09		0.69
5.1.7.6		Pyro Valves	8	0.32	2.56	5.00%	0.13		2.69
5.1.7.7		Check Valve	4	0.23	0.92	5.00%	0.05		0.97
5.1.7.8		Test Ports	6	0.12	0.72	5.00%	0.04		0.76
		[ENTER COMPONENT/SUBASSY]	0	0.00	0.00	0%	0.00		0.00
5.1.8	***PROPELLANT TANK ULLAGE VENTING SYSTEM***		62		33.82	0%	2.76	8.17%	36.58
5.1.8.1		Liquid/Gas Separator	8	0.67	5.36	25%	1.34		6.70
5.1.8.2		Iso latch valves	36	0.73	26.28	5%	1.31		27.59
5.1.8.3		Test Ports	10	0.21	2.10	5%	0.11		2.21
5.1.8.4		Propellant Orifice	8	0.01	0.08	5%	0.00		0.08
		[ENTER COMPONENT/SUBASSY]	0	0.00	0.00	0%	0.00		0.00
5.1.9	**MOUNTING/INSTALL HARDWARE**		**5**		**67.86**	**0%**	**16.96**	**25.00%**	**84.82**
5.1.9.1		Thruster Pod Structure	4	11.50	46.00	25.00%	11.50		57.50
5.1.9.2		Component Mounting Hardware	1	21.86	21.86	25.00%	5.46		27.32
5.1.9.3		[ENTER COMPONENT/SUBASSY]	0	0.00	0.00	0%	0.00		0.00

Appendix B: Propulsion MEL with Pressure-Regulated Concept (continue)

SBS ID	EQUIPMENT GROUP (TIER 2)	UNIQUE COMPONENT/SUB-ASSEMBLY (TIER 3)	Qty	Unit Mass (kg)	Basic Mass (kg)	Applied MGA / Reserves (%)	MGA / Reserves (kg)	MGA / Reserves (%)	Predicted Manuf Empty Mass (kg)
5.2.0	**AFT PROPULSION SYS (INFLATABLE SIDE)**		**461**		**439.31**	**0%**	**60.83**	**13.85%**	**500.14**
5.2.1	**THRUST GENERATION EQUIPMENT**		**12**		**55.20**	**0%**	**2.76**	**5.00%**	**57.96**
5.2.1.1		Thruster (445 N, 110 lbf)	12	4.60	55.20	5%	2.76		57.96
		[ENTER COMPONENT/SUBASSY]	0	0.00	0.00	0%	0.00		0.00
5.2.2	**PROPELLANT MGMT & DISTRIB SYSTEM**		**119**		**78.29**	**0%**	**11.27**	**14.40%**	**89.56**
5.2.2.1		Fill/Drain Valve	8	0.21	1.67	5.00%	0.08		1.75
5.2.2.2		Pyro Valves	4	0.32	1.28	5.00%	0.06		1.34
5.2.2.3		Propellant Orifice	2	0.01	0.02	5.00%	0.00		0.02
5.2.2.4		Latch Valve with Back-Pressure Relief	44	0.73	31.93	5.00%	1.60		33.53
5.2.2.5		Propellant Filter	8	0.30	2.39	5.00%	0.12		2.51
5.2.2.6		Propellant Test port	10	0.21	2.10	5.00%	0.11		2.21
5.2.2.7		Propellant Feed Lines	1	34.69	34.69	25.00%	8.67		43.36
5.2.2.8		Pressure Transducers	42	0.10	4.20	15.00%	0.63		4.83
		[ENTER COMPONENT/SUBASSY]	0	0.00	0.00	0%	0.00		0.00
5.2.3	**PROPELLANT ACQUISITION & STORAGE SYSTEMS**		**72**		**80.64**	**0%**	**10.04**	**12.45%**	**90.68**
5.2.3.1		Fuel (MMH) Tanks	4	6.91	27.64	15%	4.15		31.79
5.2.3.2		Oxidizer (NTO) Tanks	4	6.91	27.64	15%	4.15		31.79
5.2.3.3		Pressure Transducers	24	0.10	2.40	15%	0.36		2.76
5.2.3.4		Temperature Sensors	24	0.10	2.40	15%	0.36		2.76
5.2.3.5		Combined Burst Disk & Pressure Relief	8	2.27	18.16	5%	0.91		19.07
5.2.3.6		Test Ports	8	0.30	2.40	5%	0.12		2.52
		[ENTER COMPONENT/SUBASSY]	0	0.00	0.00	0%	0.00		0.00
5.2.4	**PROPELLANT RESUPPLY EQUIPMENT**		**71**		**64.30**	**0%**	**9.45**	**14.70%**	**73.75**
5.2.4.1		Propellant Latch valve	40	0.73	29.20	5.00%	1.46		30.66
5.2.4.2		Propellant Filter	4	0.30	1.20	5.00%	0.06		1.26
5.2.4.3		Propellant Half-Fluid Transfer Couplers	4	6.80	27.20	25.00%	6.80		34.00
5.2.4.4		Propellant Feed Lines	1	3.40	3.40	25.00%	0.85		4.25
5.2.4.5		Test Ports	10	0.21	2.10	5.00%	0.11		2.21
5.2.4.6		Pressure Transducers	12	0.10	1.20	15.00%	0.18		1.38
		[ENTER COMPONENT/SUBASSY]	0	0.00	0.00	0%	0.00		0.00

Appendix B: Propulsion MEL with Pressure-Regulated Concept (continue)

SBS ID	EQUIPMENT GROUP (TIER 2)	UNIQUE COMPONENT/SUB-ASSEMBLY (TIER 3)	Qty	Unit Mass (kg)	Basic Mass (kg)	Applied MGA / Reserves (%)	MGA / Reserves (kg)	MGA / Reserves (%)	Predicted Manuf Empty Mass (kg)
5.2.5	**PRESSURANT MGMT & DISTRIB SYSTEM**		**63**		**36.82**	**0%**	**4.73**	**12.83%**	**41.55**
5.2.5.1		Pressurant Fill/Drain Valve	2	0.12	0.24	5.00%	0.01		0.25
5.2.5.2		Helium Orifice	2	0.01	0.02	5.00%	0.00		0.02
5.2.5.3		Pressurant Latch valve	4	1.13	4.52	5.00%	0.23		4.75
5.2.5.4		Check Valve	16	0.23	3.68	5.00%	0.18		3.86
5.2.5.5		Helium Control Soleniod Valves	8	1.25	10.00	5.00%	0.50		10.50
5.2.5.6		Pressurant Filter	2	0.50	1.00	5.00%	0.05		1.05
5.2.5.7		Pressurant Test port	22	0.12	2.64	5.00%	0.13		2.77
5.2.5.8		Presssurant Feed Lines	1	14.12	14.12	25.00%	3.53		17.65
5.2.5.9		Pressure Transducer, Low Pressure Gas	6	0.10	0.60	15.00%	0.09		0.69
		[ENTER COMPONENT/SUBASSY]	0	0.00	0.00	0%	0.00		0.00
5.2.6	**PRESSURANT ACQUISITION & STORAGE SYSTEMS**		**14**		**15.32**	**0%**	**3.00**	**19.61%**	**18.32**
5.2.6.1		Pressurant Tanks	2	7.06	14.12	20.00%	2.82		16.94
5.2.6.2		Pressure Transducer, High Pressure Gas	6	0.10	0.60	15.00%	0.09		0.69
5.2.6.3		Temperature Sensor	6	0.10	0.60	15.00%	0.09		0.69
		[ENTER COMPONENT/SUBASSY]	0	0.00	0.00	0%	0.00		0.00
5.2.7	**PRESSURANT RESUPPLY EQUIPMENT**		**43**		**27.72**	**0%**	**5.01**	**18.09%**	**32.73**
5.2.7.1		Pressurant Latch valve	12	0.34	4.08	5.00%	0.20		4.29
5.2.7.2		Pressurant Filter	4	0.25	1.00	5.00%	0.05		1.05
5.2.7.3		Pressurant Half-Fluid Transfer Couplers	2	6.80	13.60	25.00%	3.40		17.00
5.2.7.4		Pressurant Feed Lines	1	4.24	4.24	25.00%	1.06		5.30
5.2.7.5		Pressure Transducer, High Pressure Gas	6	0.10	0.60	15.00%	0.09		0.69
5.2.7.6		Pyro Valves	8	0.32	2.56	5.00%	0.13		2.69
5.2.7.7		Check Valve	4	0.23	0.92	5.00%	0.05		0.97
5.2.7.8		Test Ports	6	0.12	0.72	5.00%	0.04		0.76
		[ENTER COMPONENT/SUBASSY]	0	0.00	0.00	0%	0.00		0.00
5.2.8	***PROPELLANT TANK ULLAGE VENTING SYSTEM***		**62**		**33.82**	**0%**	**2.76**	**8.17%**	**36.58**
5.2.8.1		Liquid/Gas Separator	8	0.67	5.36	25%	1.34		6.70
5.2.8.2		Iso latch valves	36	0.73	26.28	5%	1.31		27.59
5.2.8.3		Test Ports	10	0.21	2.10	5%	0.11		2.21
5.2.8.4		Propellant Orifice	8	0.01	0.08	5%	0.00		0.08
		[ENTER COMPONENT/SUBASSY]	0	0.00	0.00	0%	0.00		0.00
5.2.9	**MOUNTING/INSTALL HARDWARE**		**5**		**47.21**	**0%**	**11.80**	**25.00%**	**59.01**
5.2.9.1		Thruster Pod Structure	4	6.90	27.60	25.00%	6.90		34.50
5.2.9.2		Component Mounting Hardware	1	19.61	19.61	25.00%	4.90		24.51
		[ENTER COMPONENT/SUBASSY]	0	0.00	0.00	0%	0.00		0.00

Appendix C: Propulsion MEL with Blowdown Concept

SBS	EQUIPMENT GROUP (TIER 2)	UNIQUE COMPONENT/SUB-ASSEMBLY (TIER 3)	Qty	Unit Mass (kg)	Basic Mass (kg)	MGA / Reserves (%)	MGA / Reserves (kg)	MGA / Reserves (%)	Manuf Empty Mass (kg
5.1.0	FORWARD PROPULSION SYS (METALLIC SIDE		311		578.38	0%	89.88	15.54%	668.26
5.1.1	THRUST GENERATION EQUIPMENT		20		92.00	0%	4.60	5.00%	96.60
5.1.1.1		Thruster (445 N, 110 lbf)	20	4.60	92.00	5%	4.60		96.60
		[ENTER COMPONENT/SUBASSY]	0	0.00	0.00	0%	0.00		0.00
5.1.2	PROPELLANT MGMT & DISTRIB SYSTEM		151		147.01	0%	27.05	18.40%	174.06
5.1.2.1		Fill/Drain Valve	8	0.21	1.67	5%	0.08		1.75
5.1.2.2		Pyro Valves	4	0.32	1.28	5%	0.06		1.34
5.1.2.3		Propellant Orifice	2	0.01	0.02	5%	0.00		0.02
5.1.2.4		Latch Valve with Back-Relief	52	0.73	37.74	5%	1.89		39.63
5.1.2.5		Propellant Filter	8	0.30	2.39	5%	0.12		2.51
5.1.2.6		Propellant Test port	10	0.21	2.10	5%	0.11		2.21
5.1.2.7		Propellant Feed Lines	1	95.21	95.21	25%	23.80		119.01
5.1.2.8		Pressure Transducers	66	0.10	6.60	15%	0.99		7.59
5.1.2.9		Temperature Sensors	0	0.00	0.00	15%	0.00		0.00
		[ENTER COMPONENT/SUBASSY]	0	0.00	0.00	0%	0.00		0.00
5.1.3	PROPELLANT ACQUISITION & STORAGE SYS		64		197.60	0%	29.40	14.88%	227.00
5.1.3.1		Fuel (MMH) Tanks	4	23.80	95.20	15%	14.28		109.48
5.1.3.2		Oxidizer (NTO) Tanks	4	23.80	95.20	15%	14.28		109.48
5.1.3.3		Pressure Transducers	24	0.10	2.40	15%	0.36		2.76
5.1.3.4		Temperature Sensors	24	0.10	2.40	15%	0.36		2.76
5.1.19		Combined Burst Disk & Pressure Relief	0	2.27	0.00	5%	0.00		0.00
5.1.20		Test Ports	8	0.30	2.40	5%	0.12		2.52
		[ENTER COMPONENT/SUBASSY]	0	0.00	0.00	0%	0.00		0.00
5.1.4	PROPELLANT RESUPPLY EQUIPMENT		71		70.42	0%	10.98	15.60%	81.40
5.1.4.1		Propellant Latch valve	40	0.73	29.20	5.00%	1.46		30.66
5.1.4.2		Propellant Filter	4	0.30	1.20	5.00%	0.06		1.26
5.1.4.3		Propellant Half-Fluid Transfer Coupling	4	6.80	27.20	25.00%	6.80		34.00
5.1.4.4		Propellant Feed Lines	1	9.52	9.52	25.00%	2.38		11.90
5.1.4.5		Test Ports	10	0.21	2.10	5.00%	0.11		2.21
5.1.4.6		Pressure Transducers	12	0.10	1.20	15.00%	0.18		1.38
		[ENTER COMPONENT/SUBASSY]	0	0.00	0.00	0%	0.00		0.00
5.1.5	PRESSURANT MGMT & DISTRIB SYSTEM		0		0.00	0%	0.00	0.00%	0.00
5.1.6	PRESSURANT ACQUISITION & STORAGE SYS		0		0.00	0%	0.00	0.00%	0.00
5.1.7	PRESSURANT RESUPPLY EQUIPMENT		0		0.00	0%	0.00	0.00%	0.00
5.1.8	*PROPELLANT TANK ULLAGE VENTING SYSTE*		0		0.00	0%	0.00	0.00%	0.00
5.1.9	MOUNTING/INSTALL HARDWARE		5		71.35	0%	17.84	25.00%	89.19
5.1.9.1		Thruster Pod Structure	4	11.50	46.00	25.00%	11.50		57.50
5.1.9.2		Component Mounting Hardware	1	25.35	25.35	25.00%	6.34		31.69
5.1.9.3		[ENTER COMPONENT/SUBASSY]	0	0.00	0.00	0%	0.00		0.00

Appendix C: Propulsion MEL with Blowdown Concept (continue)

SBS I	EQUIPMENT GROUP (TIER 2)	UNIQUE COMPONENT/SUB-ASSEMBLY (TIER 3)	Qty	Unit Mass (kg)	Basic Mass (kg)	MGA / Reserves (%)	MGA / Reserves (kg)	MGA / Reserves (%)	Manuf Empty Mass (kg
5.2.0	**AFT PROPULSION SYS (INFLATABLE SIDE)**		**271**		**512.73**	**0%**	**82.22**	**16.04%**	**594.95**
5.2.1	**THRUST GENERATION EQUIPMENT**		**12**		**55.20**	**0%**	**2.76**	**5.00%**	**57.96**
5.2.1.1		Thruster (445 N, 110 lbf)	12	4.60	55.20	5%	2.76		57.96
		[ENTER COMPONENT/SUBASSY]	0	0.00	0.00	0%	0.00		0.00
5.2.2	**PROPELLANT MGMT & DISTRIB SYSTEM**		**119**		**138.81**	**0%**	**26.40**	**19.02%**	**165.21**
5.2.2.1		Fill/Drain Valve	8	0.21	1.67	5.00%	0.08		1.75
5.2.2.2		Pyro Valves	4	0.32	1.28	5.00%	0.06		1.34
5.2.2.3		Propellant Orifice	2	0.01	0.02	5.00%	0.00		0.02
5.2.2.4		Latch Valve with Back-Pressure Relief	44	0.73	31.93	5.00%	1.60		33.53
5.2.2.5		Propellant Filter	8	0.30	2.39	5.00%	0.12		2.51
5.2.2.6		Propellant Test port	10	0.21	2.10	5.00%	0.11		2.21
5.2.2.7		Propellant Feed Lines	1	95.21	95.21	25.00%	23.80		119.01
5.2.2.8		Pressure Transducers	42	0.10	4.20	15.00%	0.63		4.83
		[ENTER COMPONENT/SUBASSY]	0	0.00	0.00	0%	0.00		0.00
5.2.3	**PROPELLANT ACQUISITION & STORAGE SYS**		**64**		**197.60**	**0%**	**29.40**	**14.88%**	**227.00**
5.2.3.1		Fuel (MMH) Tanks	4	23.80	95.20	15%	14.28		109.48
5.2.3.2		Oxidizer (NTO) Tanks	4	23.80	95.20	15%	14.28		109.48
5.2.3.3		Pressure Transducers	24	0.10	2.40	15%	0.36		2.76
5.2.3.4		Temperature Sensors	24	0.10	2.40	15%	0.36		2.76
5.2.3.5		Combined Burst Disk & Pressure Relief	0	2.27	0.00	5%	0.00		0.00
5.2.3.6		Test Ports	8	0.30	2.40	5%	0.12		2.52
		[ENTER COMPONENT/SUBASSY]	0	0.00	0.00	0%	0.00		0.00
5.2.4	**PROPELLANT RESUPPLY EQUIPMENT**		**71**		**70.42**	**0%**	**10.98**	**15.60%**	**81.40**
5.2.4.1		Propellant Latch valve	40	0.73	29.20	5.00%	1.46		30.66
5.2.4.2		Propellant Filter	4	0.30	1.20	5.00%	0.06		1.26
5.2.4.3		Propellant Half-Fluid Transfer Couplers	4	6.80	27.20	25.00%	6.80		34.00
5.2.4.4		Propellant Feed Lines	1	9.52	9.52	25.00%	2.38		11.90
5.2.4.5		Test Ports	10	0.21	2.10	5.00%	0.11		2.21
5.2.4.6		Pressure Transducers	12	0.10	1.20	15.00%	0.18		1.38
		[ENTER COMPONENT/SUBASSY]	0	0.00	0.00	0%	0.00		0.00
5.2.5	**PRESSURANT MGMT & DISTRIB SYSTEM**		**0**		**0.00**	**0%**	**0.00**	**0.00%**	**0.00**
5.2.6	**PRESSURANT ACQUISITION & STORAGE SYS**		**0**		**0.00**	**0%**	**0.00**	**0.00%**	**0.00**
5.2.7	**PRESSURANT RESUPPLY EQUIPMENT**		**0**		**0.00**	**0%**	**0.00**	**0.00%**	**0.00**
5.2.8	***PROPELLANT TANK ULLAGE VENTING SYSTE***		**0**		**0.00**	**0%**	**0.00**	**0.00%**	**0.00**
5.2.9	**MOUNTING/INSTALL HARDWARE**		**5**		**50.70**	**0%**	**12.68**	**25.00%**	**63.38**
5.2.9.1		Thruster Pod Structure	4	6.90	27.60	25.00%	6.90		34.50
5.2.9.2		Component Mounting Hardware	1	23.10	23.10	25.00%	5.78		28.88
		[ENTER COMPONENT/SUBASSY]	0	0.00	0.00	0%	0.00		0.00