PROPULSION SYSTEM ARCHITECTURE REFUELING CAPABILITY ASSESSMENT FOR A MARS TRANSIT HABITAT CONCEPT

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ABSTRACT

A pressure-fed hypergolic bi-propellant system is the assumed propulsion approach for the Reaction Control System (RCS) used by the Mars Transit Habitat (TH), an architectural concept being traded within the NASA Moon to Mars architecture. The propellants under consideration are Monomethyl Hydrazine (MMH) and Mixed Oxides of Nitrogen with 3% Nitric Oxide (MON3), with helium pressurant.

The RCS propulsion would provide the capability for the TH to be a free-flying vehicle, which is necessary to support its notional operation across the Moon to Mars architecture. The TH concept would dock/undock with other Moon to Mars architectural elements including Gateway, Orion, Logistics Modules, Mars Propulsion System and Mars Assent/Decent Systems. When docked at Gateway, the TH propulsion system may augment Gateway stack control to achieve the required slew rates. To be capable of supporting operations over a presumed 15-year vehicle life, the TH concept assumes a refueling capability for the RCS propellants.

Bi-propellant propulsion systems have been widely used for many spacecrafts. Although the propulsion module 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 deep-space habitation application.

For the proposed bi-propellant pressure-fed system, a propellant management device (PMD) tank with overboard venting of the ullage gas has been assessed to meet the refilling capability objective of the TH concept.

This paper describes the qualitative trade assessment of the TH concept's propulsion system with regard of the propellant resupply and key-component technology maturation. The technical issues and suitable propellant tank types will be also discussed. This trade may also be extensible to other deep space habitation (or uncrewed) elements within the developing Moon to Mars architecture.

ACRONYMS

CG	Center Gravity
CLV	Commercial Launch Vehicle
CONOPS	Concept of Operations
DoD	Department of Defense
DST	Deep Space Transport
EVA	Extravehicular activity
FTC	Fluid Transfer Coupler
GNC	Guidance, Navigation and Control
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
MMH	Monomethyl Hydrazine
MON	Mixed Oxides of Nitrogen
MON3	Mixed Oxides of Nitrogen with 3% Nitric Oxide
MPS	Mars Propulsion System

NRHO Lunar Near-Rectilinear Halo Orbit
NTO Nitrogen tetroxide
PMD Propellant Management Device
RCS Reaction Control System
TH Mars Transit Habitat
TRL Technology Readiness Level

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.

The Concept of Operations (CONOPS) (2) presented in Figure 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 respect to the TH RCS operations, is briefly discussed in this paper. More details of the operations can be found in Ref. 2.

The TH and a boost stage will launch via separate Commercial Launch Vehicles (CLV) to Medium Earth Orbit (MEO). The TH will autonomously deploy and function 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 use its RCS to undock with Gateway, then transport and dock to the Mars Propulsion System (MPS).

While on 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 autonomously undock from the DST and return as a visiting vehicle to Gateway. In many ways, the TH must be designed to operate independently as a free-flying vehicle.

To be capable of supporting multiple missions and suitable of 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 (MPS shakedown, Mars transit (3)). The fluid replenishment capability will be a key feature affecting the propulsion concept trade study which will be a focus of this paper.

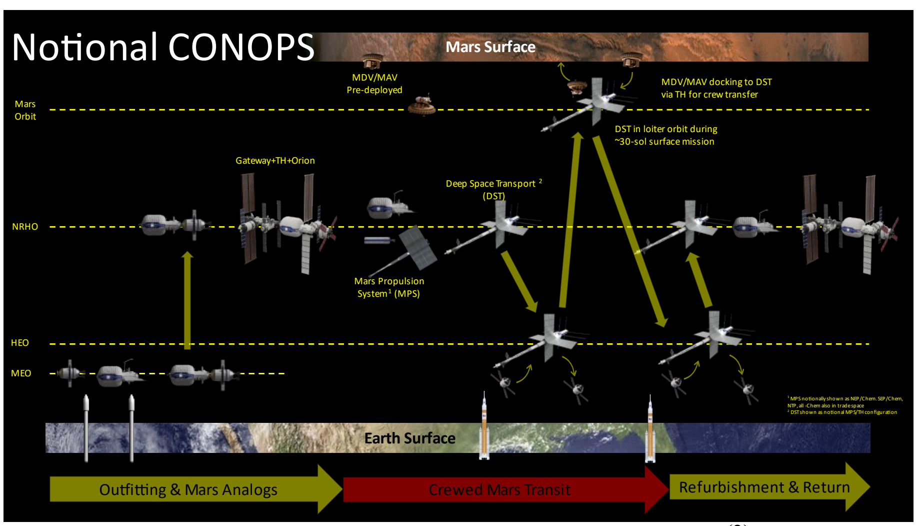

Figure 1: Notional CONOPS of TH (2)

Notional conceptual design of the TH, shown in Figure 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 end 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 around the external surface of the HT. A conceptual flow schematic will be presented in a later section of this paper.

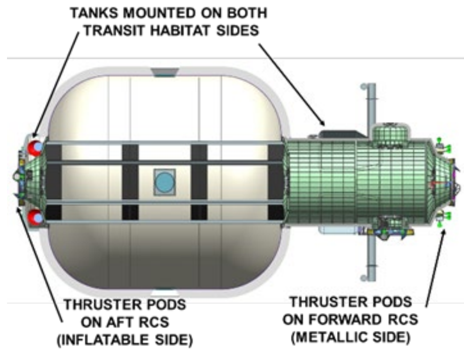

Figure 2: Notional TH Forward and Aft RCS Propulsion

(Revised figure shown on Ref. 2)

BACKGROUND ON EXISTING PROPULSION SYSTEMS WITH PROPELLANT REFILL CAPABILITIES

Extended RCS operational life with multiple propellant replenishments for the TH mission have great impacts on the selection of a concept 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 the International Space Station. Because the technology is based on Russian-Soviet experience, the Chinese system is essentially the same as the current Russian [(4)]". However, these propellant refilling techniques and propulsion components would not be suitable for the U.S. deep-space habitation 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 [(5)]. 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 a 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 possibly 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 [(6)]. The TH may not be able to use this approach and will likely need to design very low-spill automated fluid couplings and to develop a robust approach for liquid-gas separation during propellant tank venting. Technology on 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 [7].

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 [8].

PROPULSION SYSTEM AND TANK OPTIONS FOR TH

Options for the propulsion system and propellant tanks that may be suitable for propellant replenishment of the TH is depicted in Figure 3 below.

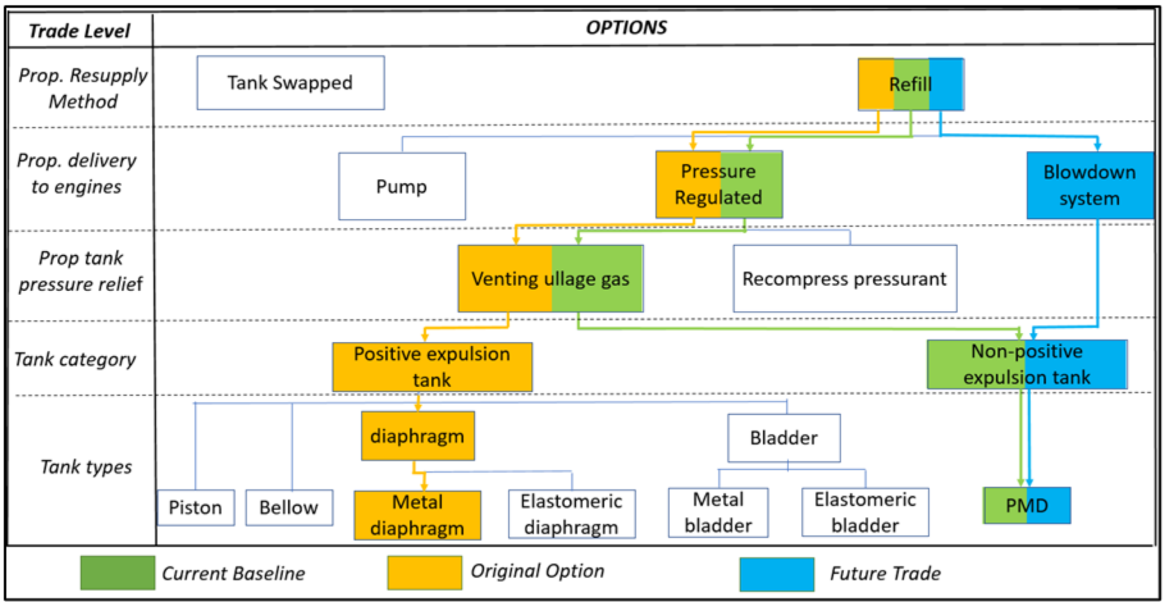

Figure 3: Propulsion Concepts & Tank Options for Trade Study

Propellants can be replenished by either swapping tanks or refilling them. Propellant refilling has been selected for TH because the propellant tanks are dispersed at the forward and aft ends of the TH. For tanks to be swapped, they would be likely mounted on pallets in a common location.

Three methods of delivering propellants to thrusters are shown on Figure 3. One method would be to pump the propellants through the feed lines to the thrusters. Another method would be to pressure-feed the propellants, using a gaseous pressurant. There are two types of pressure-fed systems: pressure-regulated and blowdown.

- A pump-fed system uses pumps to push propellants through the feed lines to the thrusters. The pump system is typically seen on vehicles requiring high thrust and high efficiency (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, however, 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.

- 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-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. Guidance, Navigation and Control (GNC) must be willing to control and operate the spacecraft with decreasing thrust and impulse bit as the mission progresses. Thrust efficiency, namely specific impulse (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 would be a suitable choice for TH RCS propulsion. A brief qualitative comparison between the pressure regulated and blowdown systems is shown in Table 1 below. A more detailed trade and assessment of these two concepts will be reported in the future.

Table 1: Key Comparisons between a Blowdown and Pressure-Regulated

<table>
<tr><th>Key Comparison</th><th>Blowdown System</th><th>Pressure-Regulated System</th><th>Rationale for Selecting Pressure-Regulated</th></tr>
<tr><td>Overboard Venting Required?</td><td>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.</td><td>Yes. Anticipation of some propellant loss and pressurant refilling because of tank ullage venting.</td><td rowspan="6">Comprehensive trade between pressure-fed and blowdown would require a more detailed design analysis.
Selecting pressure-fed system for TH is based on qualitative assessment, using our knowledge and experience for the TH class of propulsion mission. Qualitative Takeaways from our Tank Trade:
Dry Mass of a Blowdown System would likely be less than for a pressure-regulated system. However, the total wet mass of blowdown system would likely be higher.
Blowdown system may not be suitable for TH since it may require relatively high thrust, large total impulse, and relatively high delta V.
Blowdown system would require more propellants.</td></tr>
<tr><td>Pressurization system / system complexity</td><td>Less Complexity. Pressurant and propellant within a same tank. No pressurization system required. The dry mass should be significantly lower than for a pressure-regulated system; however, the wet mass will likely be higher.</td><td>More Complexity. Separate pressurization system is needed to regulate the propellant tanks</td></tr>
<tr><td>Tank size/mass</td><td>Higher. Typically, the ullage volume is at least equal to the liquid propellant volume. Subsequently, the tank size would be large and heavy.</td><td>Lower. Initial tank ullage is usually 5-10%. The pressurant enters to tank as needed for maintain a constant operating pressure within the tank</td></tr>
<tr><td>Propellant tank pressure</td><td>Decreases as mission progresses (e.g., 350 to 210 psia), propellant is removed from tank and fed to thrusters</td><td>Tank pressure is regulated to maintain the optimal value for thruster performance.</td></tr>
<tr><td>Thruster operation and performance (specific impulse)</td><td>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.</td><td>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</td></tr>
<tr><td>Total impulse requirement (thrust*time)</td><td>Best for low total impulse and low delta V applications (station-keeping is a good example)</td><td>Good for any type of mission: Thrust pulse mode, stead state (changing orbit), and high thrust demand and relatively high impulse</td></tr>
</table>

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 either metallic, polymeric, or elastomeric materials. There is a great concern with the compatibility of elastomeric and polymeric materials with oxidizer MON3 on a long-duration mission. In contrast, for a non-positive expulsion tank, gaseous pressurant (helium normally is used with hypergolic propellants) flows into direct contact with the liquid propellant. A non-positive expulsion tank employs surface tension devices, typically called a Propellant Management Device (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 2. Technology gaps for the utilization of the tanks for the TH RCS propulsion system are also highlighted in the table.

The original TH RCS, as highlighted in orange on Figure 3, has baselined metal diaphragm propellant tanks. The impermeable-barrier, positive-expulsion propellant tanks would allow for the overboard venting of only the ullage pressurant, and there is very little concern for ullage gas passing from the propellant tank into the feedline system. However, the metal diaphragm tanks are typically a single-use component, due to the permanent deformation of the diaphragm 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 metal diaphragm after refill cycles is a large concern. Perhaps, investments to test and advance the technology readiness of new metallic materials (e.g., nitinol alloy [(9)]) for tank diaphragms could make metal diaphragm tanks more viable for the TH application, and the US spacecraft industry in general. Until such time that investment is made into reusable diaphragms or other barrier devices, surface-tension PMD tanks have been tentatively down-selected for the TH. The path for this selection is shown in green on Figure 3. A pressure regulated system with PMD tanks does pose a concern for venting propellant liquid overboard during refilling of the propellant tanks. A liquid/gas separator will be required to eliminate, or at least greatly reduce, the release of liquid propellants overboard. 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 uses entirely soft-goods shells. The outer surface of the TH is typically 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, however, the vent outlet can be placed, and/or pointed, away from the TH external surface.

Table 2: Propellant Tank Assessment for Transit Habitat 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 2: Propellant Tank Assessment for Transit Habitat 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	Apollo Service Module (short mission)	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	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 ▪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). ▪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 separator ▪Minimizing impact on clean gas (pressurant) system/components ▪Flight compressor (if not venting ullage gas), compatible with prop vapor

NOTIONAL PRESSURE-REGULATED PROPULSION CONCEPT FOR TH

A flow schematic of a pressure-regulated propulsion system for TH has been conceptually formulated. Figure 4 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 current flow schematic has been developed for normal propulsion operations. Off-nominal operating conditions may lead to changes in the flow circuits and components. Revisions for off-nominal conditions and operations will be addressed in future work.

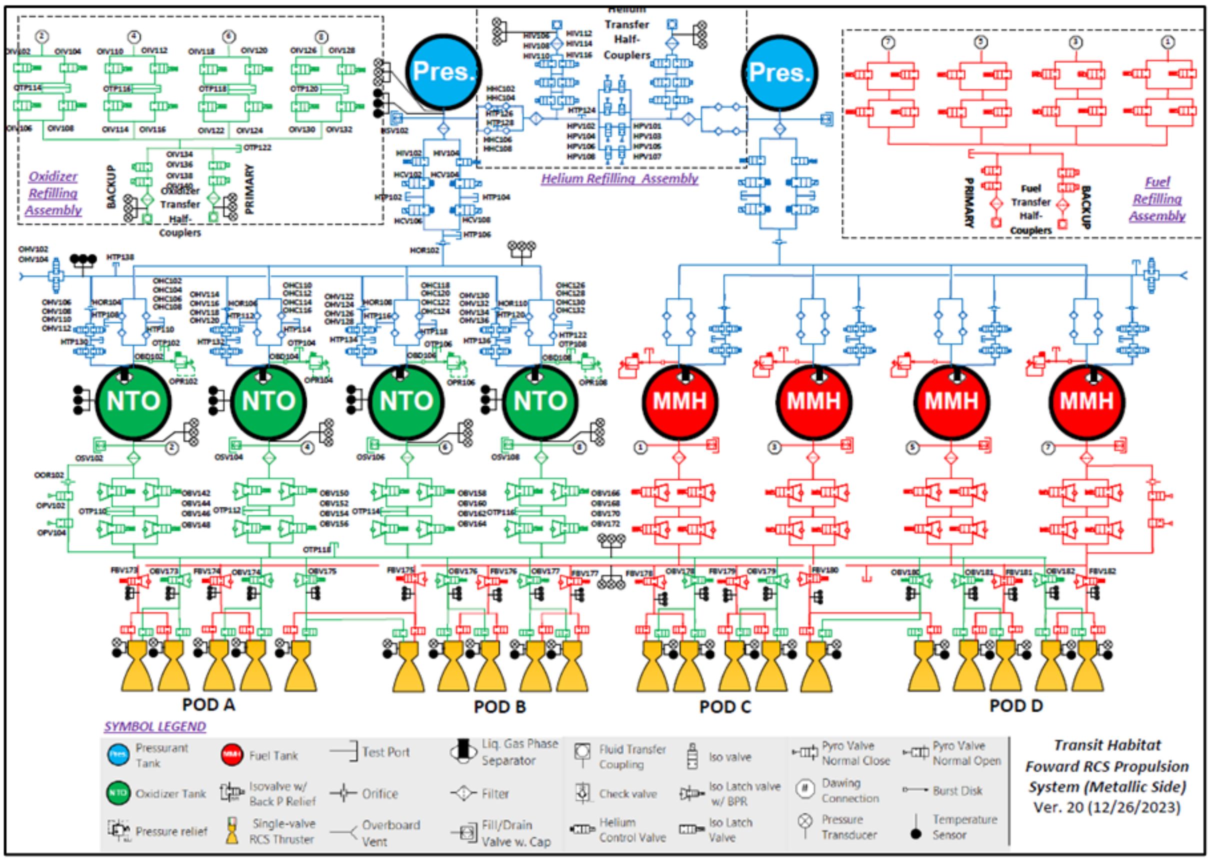

Figure 4: Pressure-Regulated Propulsion Flow Schematic of Forward TH RCS

A peer review was conducted of the flow schematic and components, to assess compliance with requirements, assumptions, and ground rules [10]. 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 also identified during the peer review.

As shown in Figure 4, the fuel and oxidizer subsystems each have their own helium pressurization subsystems that are regulated with control valves. The control valves, as opposed to pressure regulators, are selected to provide additional barriers to mitigate the catastrophic over-pressurization of a propellant tank. It is noted that a burst disk/ pressure relief valve assembly, installed just upstream of each propellant tank, would provide another layer of protection against an over-pressurization event. The burst disk/ pressure relief valve assembly would not be sized for full open pressure relief, but rather to an acceptable level.

The tanks are mounted around the external circumference of the habitat. Isolation valves with a back pressure relief feature are installed downstream of the tanks, and a common propellant manifold feeds propellant to the thruster pods. Propellant flow (fed to the thrusters or refilled from a supply vehicle) can be controlled independently for individual tanks with this arrangement. There is a possibility to serially connect the tanks, which could reduce the component count. 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) on the system. The propellant manifold distributes the propellant to thruster pairs. If an isolation valve on a thruster manifold fails closed or a thruster valve leaks, two thrusters would be removed from operation. In this event, the design still satisfies one-fault tolerance for function, since GNC can perform its function with two thrusters out. The propellant and helium lines will be sized, assuming the simultaneous operation of eight thrusters.

Regarding the propellant replenishment capability, the schematic features oxidizer and fuel refill assemblies which are connected to the outlet of the propellant tanks. The tanks can be individually refilled. Each assembly has two fluid transfer half-couplers. One 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. These couplers will be on the docking interface of the TH, similar to the couplers used on Gateway.

In contrast to defining primary and backup fluid transfer couplings, as seen on the propellant refill assemblies, a normal helium subsystem refilling requires the use of both half-couplers to transfer helium separately to fuel and oxidizer sides. In the event that one helium coupling fails (one-fault tolerance for function), helium will be transferred through the remaining coupling for both (fuel and oxidizer) pressurization subsystems. This would require pyrotechnic valve pairs, connecting both fuel and oxidizer subsystems, to be activated. The pair on a leg is composed of normally open and normally closed valves. Each leg would be opened for helium refilling to the other pressurization subsystem. At the end of the helium refilling process, the normally open valve is closed to isolate that leg to mitigate long term communication of the two parts of the system. The setup would allow to refill up to four times in the event of the coupling failure occurrence, since there are four valve pair legs. There is a concern of unwanted mixing of fuel and oxidizer within the helium pressurization subsystem once the pyro valve is activated. Check valves installed in the low-pressurant helium subsystem would mitigate the unwanted mixing of helium between fuel and oxidizer subsystems during the helium transfer.

As previously described in the propellant refilling process, ullage gas will be released overboard through a venting line assembly. The line system connects liquid/gas separator devices, which are located within the tanks, to vent outlets placed away from the TH. 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. Technology advancement of the liquid gas separator for the TH application is required. This study has baselined a gas port phase separator device [11]. This gas port phase separator device is currently designed for use in cryogenic tanks, supporting a cold-gas RCS, and would likely require a development effort for the device to be applicable to the TH mission.

Instrumentation depicted on the flow schematic is used to gather data to monitor the health of the propulsion system and to support quantity gauging of the propulsion system fluids. Hazard controls and fault, detection, isolation, and recovery (FDIR) will utilize the instrumentation. Redundancy within the instrumentation, except for the thrusters, is needed to protect one-fault tolerance for function. Fault tolerance related to thrusters is treated differently as thruster units themselves provide redundancy and fault tolerance for function. A few instruments are triple redundant, primarily if voting logic is a concern.

The flow schematic for the forward RCS propulsion has been described. The aft RCS has a similar flow schematic, except for the thruster pods. The Aft RCS Pod has three thrusters, opposed to five thrusters in the Forward RCS Pod.

The Master Equipment List (MEL) along with Mass Growth Allowance (MGA) of the TH propulsion system components, except for the propellant tanks, is based on flight-qualified hardware. ANSI/AIAA S-120A-2015 (R 2019) [12] has been used as the guideline for defining Mass Growth Allowance (MGA) percentage, that is the predicted growth allowance to the basic mass of the component.

The propellant tank shell mass has been scaled from Space Shuttle RCS tank data [(13)], using surface area and pressure ratios as the primary scaling factors. The PMD mass has been estimated from tank data on similar spacecraft propulsion systems. MGA of 15% has been applied to the tank mass. This approach results in a conservative tank mass estimate, compared to a VP/W scaling method.

Regarding propellant consumption, GNC provides a propellant estimate based on a specific impulse (Isp) of 300 sec (i.e., engine performance of 100-lbf R-4D thruster [(14)]). To account for propellant usage uncertainties, the propellant estimate also includes propellant for residual, reserve, and mixture ratio bias of 15%, 10%, and 1%, respectively. Table 3 below illustrates a breakdown of the propulsion wet mass.

Table 3: Propulsion Wet Mass Breakdown

Major Breakdown Mass	Percentage in Mass
Dry Mass	**35.2%**
Propellant Tanks	5.2%
Propellant Resupply Assemblies	3.2%
Other Components & 2nd Structure	18.5%
Ullage Venting Assemblies	2.7%
Pressurization Assemblies	4.3%
Pressurant Resupply Assemblies	1.3%
Propellants & Helium	**64.8%**
Total Percentage	**100%**

Assemblies for propellant and pressurant transfers and tank ullage are for the purpose of resupplying propellants. Their combined masses (approximately 7.2% of the wet mass or 20.5% of the dry mass) comprise a large part of overall system mass. A blowdown propulsion system has recently been considered for the TH RCS. In the blowdown system, the ullage gas venting, high-pressure helium, and the pressurant refill assemblies could be removed. The combined mass of these removed subsystem and assemblies would be 8.3% of the wet mass. However, there are a few penalties associated with a blowdown system, which include additional propellant due to degraded engine thrust and efficiency, heavier and larger volume propellant tanks, and high initial propellant tank pressure. Further trade and assessments for a blowdown propulsion system will be reported in future.

SUMMARY AND CONCLUSION

The function of the TH RCS propulsion is to provide free-flying spacecraft capabilities and to augment Gateway stack control when docked on Gateway. The requirements for extended operational life and multiple propellant replenishment have significant impacts related to selecting a propulsion system concept and components for the RCS. Propellant refilling techniques and propulsion components used on Russian segment of the ISS are not suitable for the deep-space habitation application.

A pressure-regulated hypergolic bi-propellant system has been down selected for TH RCS. A peer review has been 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 TH propulsion system design. Instrumentation laid out on the schematic is used to gather data to monitor the health of the propulsion system and to support quantity gauging of the propulsion system fluids.

Metal diaphragm and non-positive-expulsion PMD propellant tank system has been traded against each other, with the PMD architecture being selected. Venting ullage gas (a mixture of helium and propellant vapor) 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 further advanced.

An estimate of the propulsion wet mass is presented in the paper for the PMD tank architecture. A blowdown propellant tank architecture is currently being considered as an alternative to the PMD tank architecture. There may be relatively significant dry-mass-reduction benefits, associated with blowdown architecture; however, the propellant mass of a blowdown system would likely increase. The blowdown propulsion system architecture for the TH will be further evaluated in future work

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