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A Single Stage to Orbit Design for a Hybrid Mars Ascent

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A Single Stage to Orbit (SSTO) hybrid propulsion system has been previously studied as an option for a conceptual Mars Ascent Vehicle (MAV). The hybrid motor uses a wax-based fuel developed specifically for this application, so it can take advantage of a single port design. The oxidizer is Mixed Oxides of Nitrogen (MON-25). Higher Nitric Oxide concentrations have been discussed in the past, however, the lower temperature capability is no longer needed. The MAV Payload Assembly (MPA), which would house the Orbiting Sample (OS) has changed substantially from previous iterations and has become more compact. Benefits of the hybrid option include its predicted low temperature behavior, high performance and ability to restart (enabling the SSTO). However, the hybrid technology remained at a relatively low Technology Readiness Level (TRL). In an attempt to increase the TRL, a technology development program has been underway for the past four years. The results of the technology development program are now being incorporated to an updated concept for a hybrid Mars Ascent Vehicle, with the eventual goal of informing a hybrid propulsion design that closes under the guidelines currently envisioned for a potential Mars Sample Return campaign.

This paper focuses on the hybrid propulsion system design and the preliminary results from the first part of the FY19 technology development program (October 2018 to July 2019) and includes some results from a Preliminary Architecture Assessment (PAA) study. In the PAA, experts from all relevant subsystems (propulsion, avionics, GN&C, structures, thermal, etc.) are brought together to determine an updated vehicle design. The PAA is being run out of Marshall Space Flight Center (MSFC) in coordination with the Mars Sample Return study lead by the Jet Propulsion Laboratory (JPL). Currently, it is thought that the Mars Ascent Vehicle would be housed in a Sample Retrieval Lander (SRL), along

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with a fetch rover. The SRL would be responsible for several crucial functions on the MAV including heating, erection and providing the ignition signal.

This paper will also outline the future testing and path forward through the rest of the fiscal year. This includes full scale testing at Whittinghill Aerospace, hypergolic additive testing at Purdue, evaluation of adding hypergolic additives to a full-scale grain. A hybrid fuel formulation has been updated with a reduced regression rate, which again was developed by Space Propulsion Group. This design will be used to determine the benefits of a hybrid versus solid propulsion system for a MAV, as they fit into the larger vision for a potential Mars Sample Return campaign.

I. Nomenclature

6DOF = Six Degree of Freedom
AFT = Allowable Flight Temperatures
GN&C = Guidance, Navigation and Control
GOx = Gaseous Oxygen
IMU = Inertial Measurement Unit
Isp = Specific Impulse
JPL = Jet Propulsion Laboratory
LITVC = Liquid Injection Thrust Vector Control
MAV = Mars Ascent Vehicle
MAVRIC = Mars Ascent Vehicle Research and Innovation Campaign
MLI = Multi-Layer Insulation
MMH = Monomethylhydrazine
MON-25 = Mixed Oxides of Nitrogen (with 25% Nitric Oxide)
MPA = MAV Payload Assembly
MRN = Mars Relay Network
MSFC = Marshall Space Flight Center
MSR = Mars Sample Return
NEPA = National Environmental Policy Act
NO = Nitric Oxide
OS = Orbiting Sample
PAA = Preliminary Architecture Assessment
PRT = Platinum Resistance Thermometers
RCS = Reaction Control System
SPG = Space Propulsion Group, Inc.
SRL = Sample Retrieval Lander
TCS = Thermal Control System
TEA/TEB = Triethylaluminium/Triethylborane
TRL = Technology Readiness Level
WASP = Whittinghill Aerospace

II. Introduction

The Mars Ascent Vehicle (MAV) is a part of the proposed Mars Sample Return (MSR) campaign. The first part of the Mars Sample Return is the Mars 2020 lander, which is being built and will launch in 2020. Mars 2020 will extract and package rock and soil samples from various locations and leave them on the Martian surface.

The Mars Ascent Vehicle is a proposed mission to be launched as part of the Sample Retrieval Lander (SRL). A Sample Fetch Rover, which would also be delivered to Mars with the SRL, would pick up the cached samples and deliver them to the SRL, to be inserted in the Orbiting Sample (OS) container by a Sample Transfer Arm. After the samples are secured in the OS, the MAV will launch it into an orbit around Mars. An Earth Return Orbiter, also proposed, would retrieve the OS from orbit and send it back to Earth. For further details on the potential MSR program, see Reference 1.

Over the last two decades there have been many studies and development efforts for a Mars Ascent Vehicle. These studies evaluated solids, bi-propellant liquids, spinning solids, gelled propellants, monopropellants, and recently hybrid rocket concepts. For a detailed review, see Reference 2. At the end of this reference, Shotwell discusses the trades that led to the current hybrid propulsion MAV effort.

Further investigation in that trade suggested a single stage to orbit hybrid rocket vehicle that is capable of a restart could be advantageous in the MAV role. This hybrid concept uses a liquefying hybrid fuel. During investigation of a frozen pentane hybrid, the pentane was found to have a much higher regression rate than classical hybrid regression rate theory predicted (see Reference 3). It was discovered that a liquid layer formed on the surface and was entrained into the flow and combusted away from the wall (see Reference 4), dramatically increasing the regression rate. Later, other materials that had that similar properties were investigated and the paraffin-based fuels were discovered (see Reference 5). The higher regression rate allows for the use of a single port in the MAV design. Space Propulsion Group developed the fuel for this application (see Reference 6). MSFC has been developing the processing for the full-scale fuel grain (see Reference 7).

Potential benefits of the hybrid concept included low temperature capabilities, higher Specific Impulse (Isp) and no need for staging. However, the hybrid system had a lower Technology Readiness Level (TRL) than some of the other traded propulsion techniques. Since the launch was proposed to be more than a decade away, there was time to develop the hybrid technology in the interim. The goal of this effort was to raise the TRL to a level (~6) that would allow its consideration for the potential flight mission. That development included solid fuel and hypergolic development, motor firings at vendor sites and an Earth demonstration of that technology in a launch called Mars Ascent Vehicle Research and Innovation Campaign (MAVRIC). Reference 8 goes into detail on those plans.

While in the planning stages of MAVRIC, the proposed launch of a MAV moved forward to possibly as early as 2026, significantly reducing the window for hybrid propulsion technology development. A decision was made to scrap work on the MAVRIC and move into launch trades. A preliminary review was held by MSFC Advanced Concepts Office, see Reference 9. That study led to the PAA: a larger vehicle study between a two stage to orbit solid and the single stage to orbit hybrid propulsion systems. Tentatively, a down selection between the solid and hybrid concepts is scheduled for late 2019.

The MAV hybrid effort has been a multi organizational effort, with collaborators at NASA's Jet Propulsion Laboratory (JPL), Marshall Space Flight Center (MSFC), White Sands Test Facility (WSTF), Ames Research Center (ARC), and Langley Research Center. Additionally, Whittinghill Aerospace (WASP), Space Propulsion Group (SPG), Purdue University and Penn State have all contributed.

III. Hybrid Technology Development for PAA

In the lead up to and during the PAA, there has been substantial hybrid testing and analysis completed.

A. Purdue University

In 2015, there was a trade study conducted at MSFC to evaluate the best ignition system for the hybrid propulsion system. The best solution was a hypergolic additive in the fuel, so that ignition was accomplished by simply opening the oxidizer valve. That trade study led to two universities, Penn State and Purdue, investigating solid hypergolic additives (see References 10 and 11). Purdue continued testing the hypergolic solids in sub-scale motors (see References 12, 13, and 14) with successful ignition and re-ignition at atmospheric conditions. Upcoming testing includes ignition in a vacuum chamber. Ignition in a vacuum is a key milestone, since hypergolic ignition time is a function of the ambient pressure, the higher the pressure, the shorter the reaction time. Martian ambient pressure is quite low, therefore, vacuum performance of candidate hypergolic solids will be critical to understanding their performance in a potential flight configuration.

B. Space Propulsion Group (SPG)

SPG has developed the original MAV fuel formulation, SP7 (see References 6 and 15). SPG has done testing on a 3 inch and an 11 inch diameter scale. The 3 inch testing was for ignition characteristics and burn rate characterization. The 11 inch testing was full scale at the time in a composite overwrapped case, see Figure 1.

Figure 1 SPG Testing with Composite Case

After recent testing indicated the hybrid design would package better with an even lower regression rate fuel, SPG developed a reduced regression rate formulation (85% of SP7), called SP7A. Sub-scale (3 in) testing was used to confirm the desired regression rate was achieved. Three tests at each the predicted, a higher and a lower regression formulation were completed it Jan of 2019. More testing of SP7A is currently in progress to add slightly more statistical significance to the data set.

Since the hybrid rocket is a single stage to orbit vehicle, mass is at a premium, and conventional solid rocket case flanges required to leave area for removal of a propellant mandrel would be too heavy. SPG has investigated processing to incorporate the motor into a titanium shell (domes, case and nozzle), which would be welded together after the grain was inserted. This assembly would be overwrapped for lighter weight motor case.

Finally, SPG is currently investigating fuel processing and doing CFD simulations to help understand the heating inside the motor. This includes understanding the nozzle design through the long first burn, coast and second burn.

C. Whittinghill Aerospace (WASP)

Whittinghill has completed about half a dozen large scale motor tests (see Reference 16). This testing has demonstrated good stability and restart capabilities. Figure 2 shows the longest test to date with SP7 and MON-3.

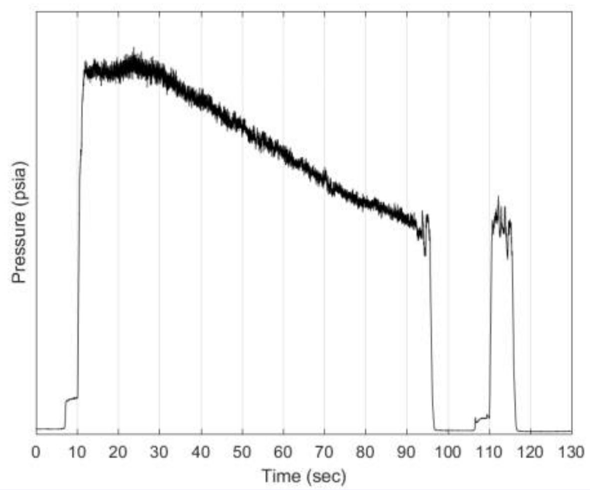

Figure 2 - WASP FT01 Chamber pressure (Reference 16)

The last test, FT03, was fired at the planned MAV operating temperature of -20C with SP7 and MON-25. It was a stable test. However, it suffered from high nozzle erosion similar to other tests. The MAV operational temperature range has implications to the motor processing. SP7 (and SP7A for future tests) have a high coefficient of thermal expansion and would separate from the case at -20C if assembled at 20C. That could lead to grain cracking since the wax base fuel would be unsupported during ignition. This scenario led to assembly of the FT03 grain and motor case at -20C. Good grain integrity was observed over most of the grain, with the exception of known pretest flaws due to an issue with the cold temperature assembly. FT04's grain (the first full scale test with SP7A) was assembled at -43C to ensure the grain was in compression over the larger cycling temperature expected on Mars inside the SRL. That motor will be fired in July of 2019.

IV. Preliminary Architecture Assessment (PAA)

The PAA is a process initiated at MSFC to explore whether the hybrid and/or the solid concept could accomplish the mission.

A. Process Overview

The MSR study team wished to trade the SSTO hybrid propulsion ascent vehicle with a two-stage solid propulsion vehicle. The purpose of the Preliminary Architecture Assessment (PAA) was to develop conceptual designs for both vehicles, estimating mass, power, and performance. The results would be used as a basis for the comparison prior to selecting the best propulsion system. The PAA study team was a multidisciplinary design team from multiple NASA centers.

The two concepts were developed in parallel. Each concept was designed iteratively, with an initial design undergoing a 3DOF analysis, adjusting design variables based on performance in the 3DOF, then undergoing a 6DOF analysis and a dispersion analysis. Both vehicles met the initial design requirements for the Mars ascent.

B. Propulsion

The hybrid MAV design that evolved during the PAA Study can be seen in

Figure 3 and some of the highlights and challenges of the design are discussed below. The vehicle consists of a single MON-25 tank and a hybrid motor with a center perforated fuel grain (wax-based SP7A). The system is pressure fed, with the helium pressurant also being used for RCS propellant. Details of the components are schematically shown in

Figure 4. The selected oxidizer-to-fuel ratio of the system coupled with the regression rate of the fuel, leads to a specific length to diameter ratio requirement of the fuel grain. This form factor allows for various components, in this case the helium and ignitor fluid tanks, to be housed around the combustion chamber. This unusual configuration is driven by the geometric constraints of the SRL, which houses the MAV. The volume available to the MAV is approximately 2.8 m of length by 0.57 m in diameter and the maximum gross lift off mass is 400 kg.

The nozzle performance was optimized using Two Dimensional Kinetics, in the middle of the GN&C Six Degree of Freedom (6DOF) analysis. Up until that point, an estimate was used for the nozzle efficiency, predominately based on losses for a reduced length bell nozzle. The TDK analysis indicated the estimated nozzle efficiency was too high (by ~4%) and was not adequately capturing the physics in the nozzle flow. This lead to a resizing of some of the propulsion components and decreasing the Oxidizer to Fuel ratio (O/F). This makes it more fuel rich, which should help reduce the excessive nozzle erosion seen in tests to date (see pressure decay in Figure 2). The lower O/F will not be demonstrated in FT04 (motor test B), since it was designed before the TDK analysis. FT04 does have a different nozzle material than what has been used on previous tests is being planned. These changes have not yet been evaluated by GN&C, but the impact on the 6DOF should be minimal, assuming the motor is sized to provide the same change in velocity.

The ignition system design continues to evolve. While a solid hypergolic ignition is still seen as desirable, it is considered a substantial development. Hybrid motor tests at SPG and WASP have included pyro igniters, gaseous oxygen (GOx) addition, hybrid heater motors and triethylaluminium/triethylborane (TEA/TEB) with a GOx lead. Development testing has shown that with the designs tested so far, heat addition in the head end of the motor has been needed to maintain motor stability (see References17 and 16). This has been accomplished by leaving the ignition fluid, or another heat source, on throughout motor operation. TEA/TEB is pyrophoric with oxygen, and slightly reactive with N_2O_4, and testing at Whittinghill in a vacuum environment has not shown it to be reactive enough to initiate combustion without the oxygen lead in the motor configuration. While it is not impossible to add a small GOx source to the flight design, its low density and the increased complexity are not desired. An alternate hypergolic ignition fluid (to TEA/TEB) has been tested; however, initial results indicated that the ignition delay time was too long for the injector design tested (with MON-25 at -20C) to be useful for MAV.

The next potential solution is to use Monomethylhydrazine (MMH) as an ignition fluid. MMH has shown hypergolic ignition in bipropellant thrusters with MON-25 at temperatures below the desired operational temperature of the MAV (down to -40C, see Reference 18) under vacuum conditions. Whittinghill has recently obtained permits to use MMH at their Mojave, CA test facility. It may be considered for future tests. Until that time, TEA/TEB/GOx is being used for ground testing. The low ignition pressure seen in Figure 2 from ~5 to 10 seconds is the TEA/TEB/GOx combustion, before the MON-25 comes on. No attempts have been made up to this point to reduce the ignition delay to something representative of what could be used for flight. That ignition time will be reduced in the next test: FT04/Motor B.

The helium pressurant is loaded at 10,000 psi in four tanks at Earth ambient conditions. The high pressure is required for low temperature operation and compact packaging. The hybrid MAV concept is designed for operation at -20C, which drives the sizing of the high-pressure tanks. However, there is currently substantial margin in the pressurization system. Analysis has shown that the pressurization system is capable of operating at -40C and it has been suggested that the system could be lightened by reducing the size of the tanks or reducing the number of tanks to three for operation at -20C. Since the MAV is heated by the SRL prior to operation, it is possible that the helium tanks could be heated to a higher temperature than rest of the propulsion system to further reduce the mass of the pressurization system.

There are several components that will require development for the MAV application. The high-pressure pressurant regulator will require further development due to the high pressure range and the low temperature range. One risk of the low temperature operation is the choice of seat materials for the regulators. Analysis has shown that if the mission profile were to begin at -40C, the first stage regulator would drop below -80C. Using an initial temperature of -20C, the helium temperature will drop to just below -60C. Both of these temperatures are below the capability of some seat materials existing in relevant high-pressure regulator designs. Similarly, the low-pressure regulator components will require development to survive the cold helium flow. While a material solution could be found, a lower development risk solution may be to raise the temperature of the helium tanks just prior to use, which would bring the pressurant flow temperature within current specifications of the dome regulator and reduce concerns with low temperature seat material development. Several options will be explored as the propulsion system matures.

A pyrovalve isolates the helium tanks from the MON-25 tank from the point in time at which the tanks are loaded until just before launch from the Martian surface. This component may require further development to deal with the low temperatures during operation, where the helium temperature dips.

The MON-25 tank has several functions, including containing the oxidizer and taking primary structural loads. Current iterations on the design have led to aluminum liner with a carbon fiber and epoxy composite overwrap to provide the needed structural rigidity. The tank will also include a propellant management device to help with the position of the oxidizer at the start of the second burn and inhibit propellant dropout and vortexing. Baffles will be included in the tank to mitigate propellant slosh. Analysis has been done of several baffle designs and the selection of a design will depend on results from a 6DOF trajectory analysis of the flight to determine the amount slosh damping required.

The main oxidizer valve is another component which would require development. Light-weight, fast response valves like the one in this concept, have not been built since the Space Shuttle program. The valve opening time will drive the complexity of the design in order to meet the desired propulsion ignition time.

Assuming the MAV hybrid propulsion concept is selected, development of the long lead components discussed above: the pressure regulators, main oxidizer valve and oxidizer tank, would need to be initiated.

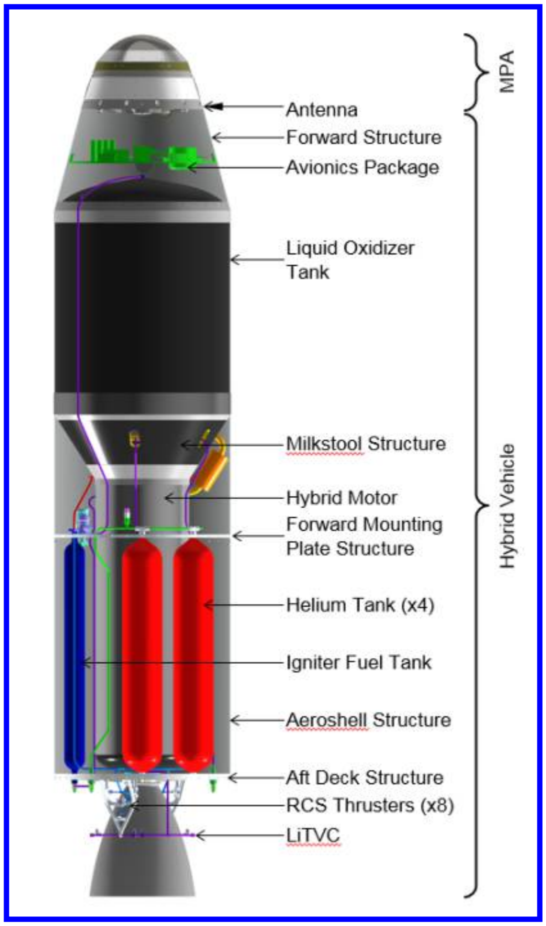

Figure 3 MAV Hybrid Motor Concept

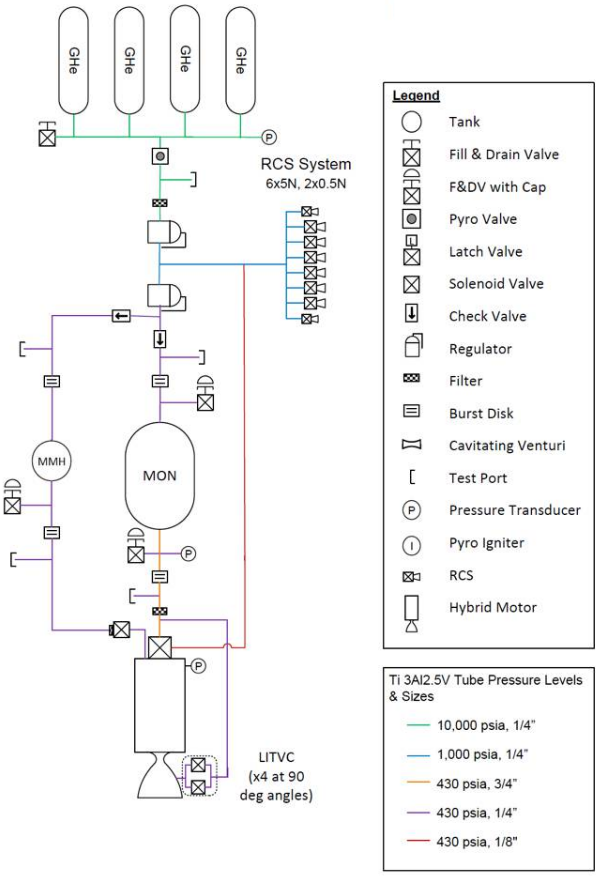

Figure 4 MAV Hybrid Rocket System Schematic

The reaction control system (RCS) in this design is a blow down system, which takes advantage of the helium already present on the vehicle as the oxidizer pressurant. It does not add significant mass or complexity to use Helium for RCS. Slight modifications to the high TRL, lightweight valves used on the LITVC system, have been suggested for these cold gas thrusters. The downside of using helium gas is the specific impulse falls with the initial gas temperature, and that falls as the helium is vented to pressurize the oxidizer tank. The initial RCS configuration is shown in Figure 5.

RCS usage during the first motor burn is for roll control only. During the coast phase, the RCS is responsible for maintaining the vehicle attitude. At the end of the coast, the settling thrusters are activated to provide the acceleration necessary to get the oxidizer in position for the second burn.

There is an opportunity to use the residual pressurant gas in the helium tanks and oxidizer tank to do fine corrections in the orbital placement after the second burn.

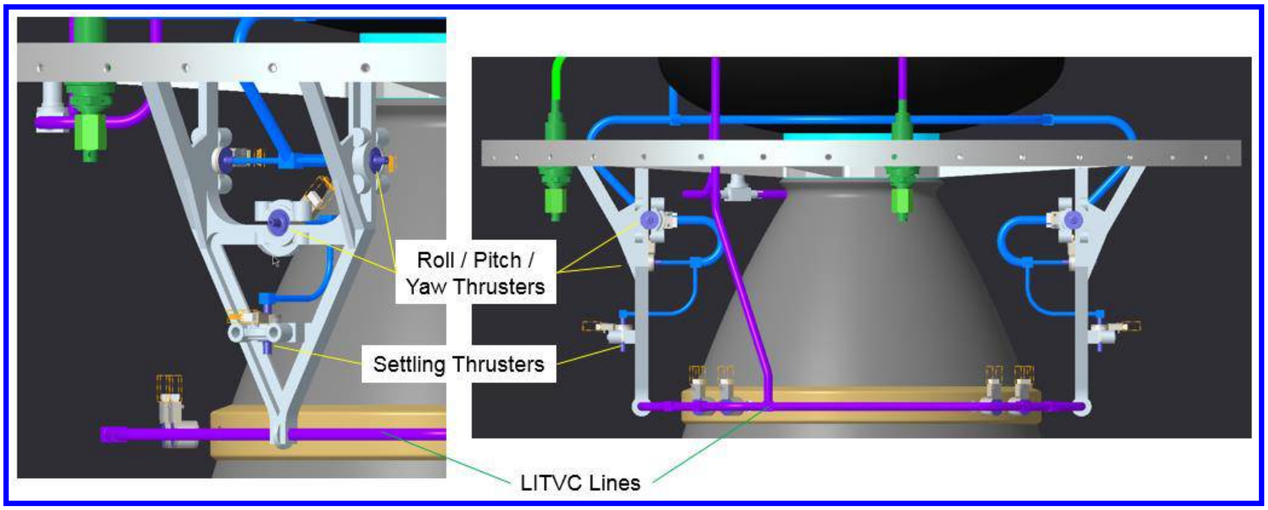

Figure 5 RCS Configuration

Thrust vector control trades were done in 2015 that selected Liquid Injection Thrust Vector Control (LITVC) as the baseline technique. LITVC is based on injecting a fluid into the expansion cone of a nozzle. The injected liquid becomes a gas and forms a disturbance in the flow thru the nozzle. A shock forms and the resulting pressure behind the shock is higher than the rest of the nozzle and pushes the nozzle in that direction. It was seen as particularly well suited for the hybrid MAV, since a liquid was already being carried on board. However, it means that an expendable is required to accomplish thrust vector control. This was to be reevaluated during the current PAA to see if the required vectoring was too high as to where a different nozzle vectoring concept needed to be deployed. Results at this time indicate that LITVC is still the better choice for nozzle vectoring. However, a trapped ball design, where the nozzle pivots and is constrained via a ball in a socket, as is being considered for the Solid MAV design, can be considered as an alternative if issues with the LITVC system arise.

LITVC testing has been conducted at WASP and SPG with MON-3 in short expansion cone nozzles (designed for Earth based testing). WASP measured the side loads and that data has been compared to CFD models developed at MSFC and has been shown to match rather well. Vacuum testing was planned at White Sands Test Facility to demonstrate LITVC performance with MON-25 and a full expansion nozzle; however, that testing was postponed until after a propulsion system has been selected.

LITVC is a moderate TRL Thrust Vector Control system and have been used in the Titan Solid Rocket Boosters. The system relies on fast actuation solenoid valves, which have been demonstrated in the ground based testing completed at WASP. The injectant fluid comes from the MON-25 oxidizer tanks thru a supply manifold, see Figure 6. The LITVC injection ports are spaced around the perimeter of the nozzle.

The LITVC valves occur in pairs around the nozzle to enable two different deflection angles (Figure 6). If a single valve is opened, approximately 1° of deflection is achieved. If both are opened, approximately 2° of deflection is possible. The configuration enables the use of existing valves with minor modifications, enables multiple deflection angles and provides a potential for some redundancy. It should be noted that the LITVC system offers liquid injection at discrete angles around the nozzle (where the valves are located). For vector angles between the valves, it is possible to operate pair of adjacent valves together with liquid injection pulses, but this comes with a reduced performance compared to vectoring in plane with a valve. Initial performance predictions have been made with CFD, but have not been confirmed experimentally.

A common LITVC / RCS controller is proposed to drive the valve coils for all RCS and LITVC valves. The valve power draw is being optimized (hold current versus pull-in current). The controller is powered by a main bus (vehicle batteries) and communicates with flight computer via RS422 protocol (monitoring commands, health and status). LITVC command resolution from 5% to 100% is limited only by size of command word and the requests from the GN&C system.

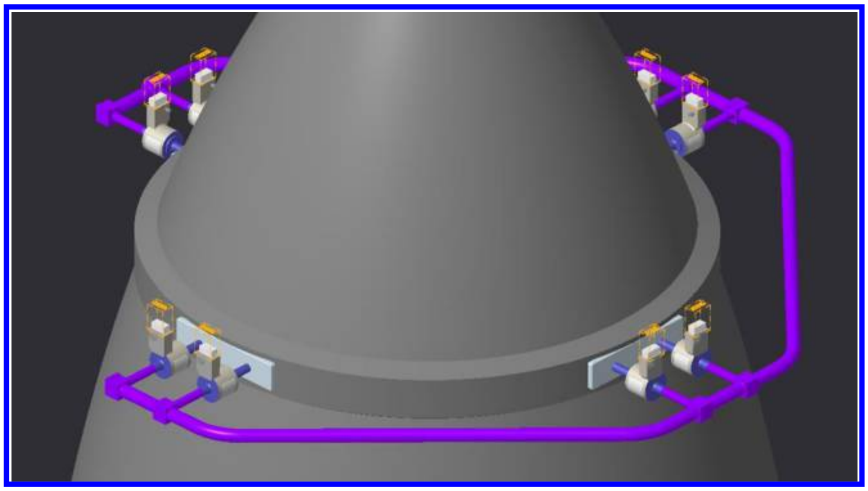

Figure 6 LITVC Valves Supplied MON-25 Through Common Manifold

C. Thermal

The thermal analysis of the hybrid MAV configuration considered three individual phases of the mission timeline: cruise during Earth-Mars transit, Mars surface operations, and Mars launch and ascent. During cruise and surface operations, the MAV is stored in an enclosure of the SRL known as the igloo. This igloo provides thermal insulation and as well as additional environmental protection from both deep space and the Martian environment. A system of thermal heaters have been sized to maintain Allowable Flight Temperatures (AFTs) of the internal MAV components during these times. Figure 7 below shows the igloo within the SRL.

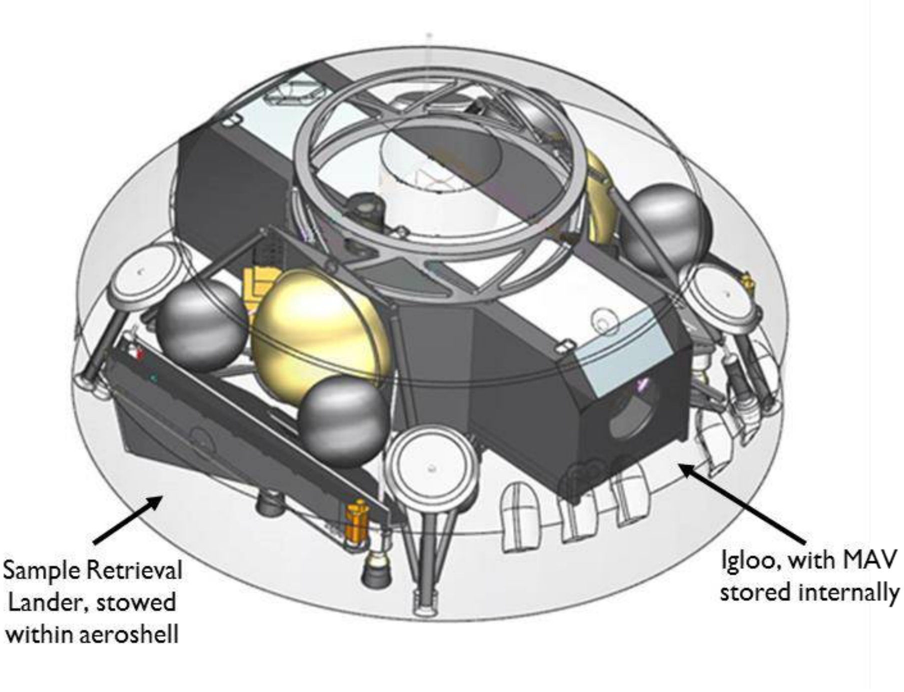

Figure 7 MAV Stowed in Igloo on SRL

While on the surface of Mars, the MAV external thermal environment is represented by the temperature of the igloo. This temperature is modeled as a boundary at -62.5C. The onboard Thermal Control System (TCS) is employed to maintain a nonoperational temperature of -40C and an operational temperature of -20C. The same heaters would be used to maintain these Allowable Flight Temperatures (AFTs), with Platinum Resistance Thermometers (PRTs) to monitor the temperature and provide feedback to the SRL. Figure 8 below gives an example of some of the types of heaters and PRTs that can be used in this application.

Figure 8 Potential Heaters/PRTs for use on MAV

The current design includes 17 heater control zones, with each zone containing one or more heaters. Different heater sizes and shapes are required to accommodate various components such as tanks and avionics. Most heater options are available from commercial off-the-shelf providers. Wherever possible, the TCS will be wired in parallel to give a form of fault tolerance. In addition to heaters, the TCS employs Multi-Layer Insulation (MLI), low emissivity tapes, carbon dioxide gap insulation, and a traditional Thermal Protection System (TPS). Figure 9 below outlines the layout of the TPS and TCS on the hybrid MAV.

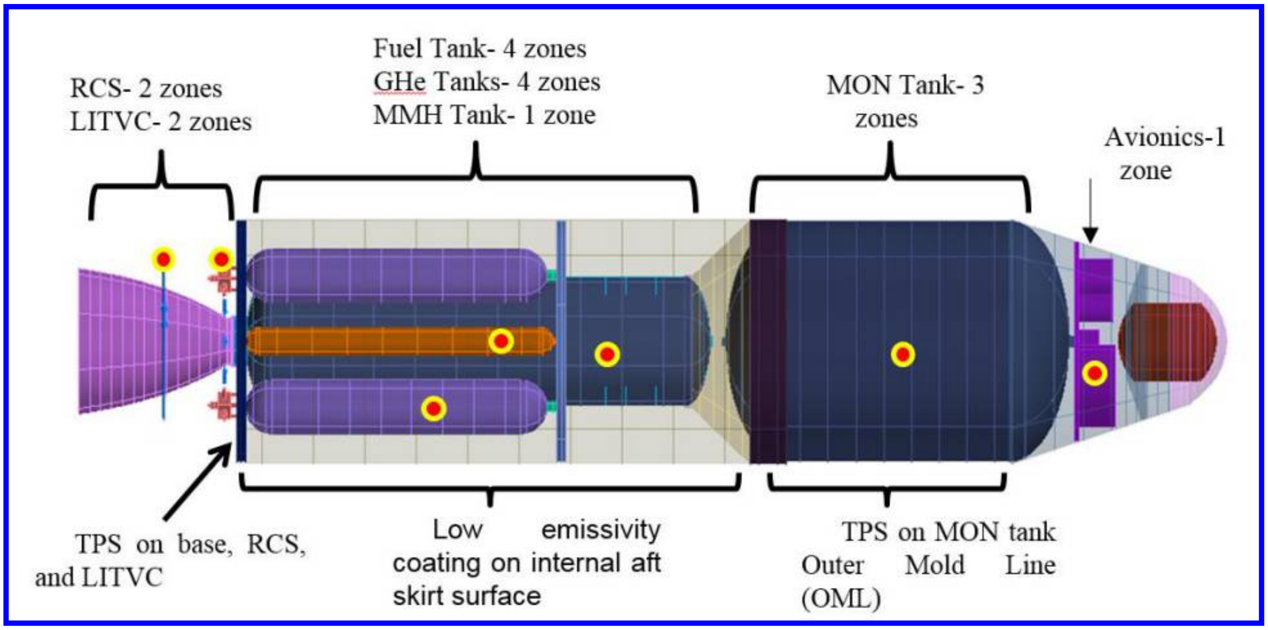

Figure 9 Hybrid MAV Thermal Protection System (TPS) and Thermal Control System (TCS)

The TCS design features a number of relatively high TRL components to regulate the temperature of the vehicle while both stowed and during flight. The MLI will be used in avionics interfaces with multilayered sheets, similar to what is currently used on the International Space Station (ISS). Low emissivity tapes and films will be used to cover heater elements and a number of interior MAV surfaces in a similar fashion to the Hubble Space Telescope (HST) and Mars Exploration Rover.

While on the Martian surface, the volume between the the MAV and igloo surface would be filled with carbon dioxide. This will act as an insulator to prevent natural convection. Two configurations were examined for this study: an insulation gap of 5cm and an insulation gap of 10cm. The 10 cm configuration features a Mylar blanket to further reduce convection. Figure 10 displays the MAV within the igloo.

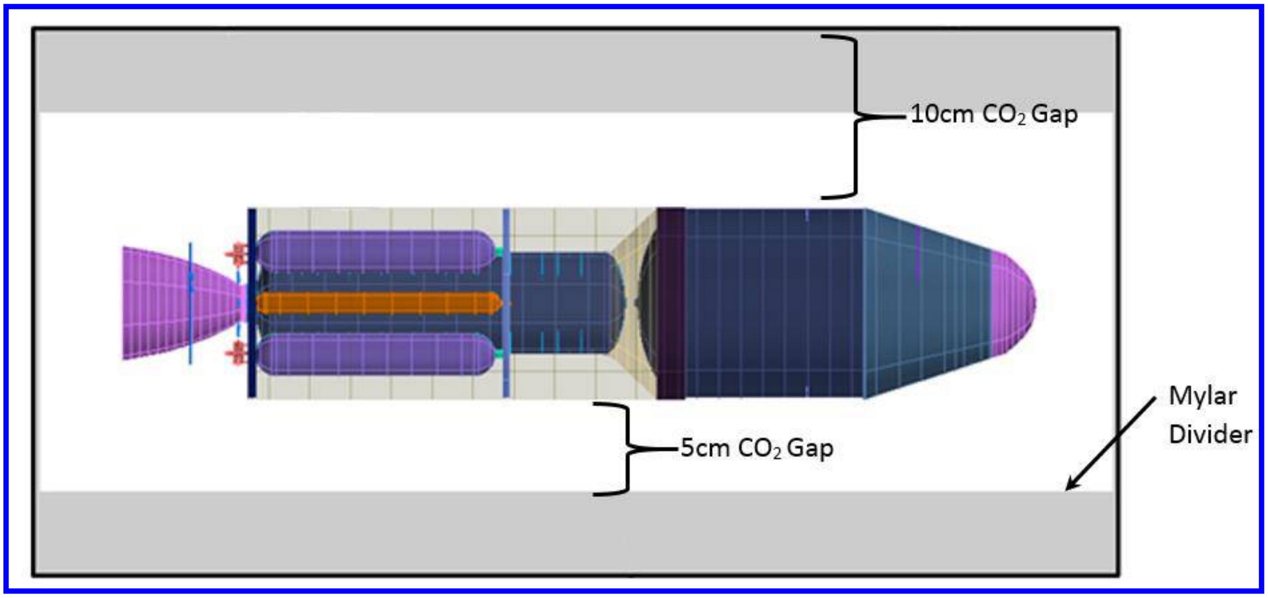

Figure 10 MAV Within Igloo

The TCS design also features a traditional TPS with thermal insulating materials. This TPS features a sheet of P50 cork covering the aft plate to protect it from plume heating. If necessary, a layer of Spray On Foam Insulation (SOFI) is a potential option to be used on the Outer Mold Line of the MON-25 tank as well as RCS and LITVC components to provide insulation from aeroheating and radiation heating. These insulating materials have been used prior on Delta IV, Saturn V, and Space Shuttle launch vehicles.

A thermal analysis of the TCS for both 5 cm and 10 cm igloo gap configurations found that during surface operations, the 5 cm gap design used approximately 60% more power than the 10cm gap design. This applied to both the operational and non-operational conditions. Despite this, the TCS in both designs meets the MAV AFTs for cruise, surface, and launch and ascent phases.

The wax based hybrid fuel cannot withstand large temperature gradients. The SP7A solid component of the hybrid motor has a maximum radial temperature gradient change of 10C/hr, assuming it's the same as the SP7 values(see reference 19). The thermal analysis found that during warmup from nonoperational to operational temperatures, both the 5cm and 10cm gap designs fell below this temperature gradient. Ultimately, a peak power draw from the thermal system was found to be 210W assuming worst case high voltage of 36VDC (with 28 VDC assumed as nominal).

D. Structural

The structural analysis was broken up by propulsion and vehicle components. Vehicle components include the forward structure, the interface between the oxidizer tank and motor (aka the milk stool) and the aeroshell. The propulsion components loads may be dictated by the pressure loads in the MON-25 tank, the hybrid motor and the pressurant tanks.

The propulsion tanks are all composite overwrapped pressure vessels (COPV) and were analyzed as such. The MON-25 tank has an aluminum liner. To handle the MON-25 reacting to vehicle movements, there are slosh baffles. It is likely that the baffle design shown in Figure 11 will change to where the baffles are supported by an internal structure instead of directly attached to the tank, since the baffles would keep the tank from locally expanding near the baffle and possibly result in the composite pulling away from the aluminum liner. The design shown here is representative of what the baffles could look like, but the actual configuration will be determined after the trajectory and slosh damping requirements are determined.

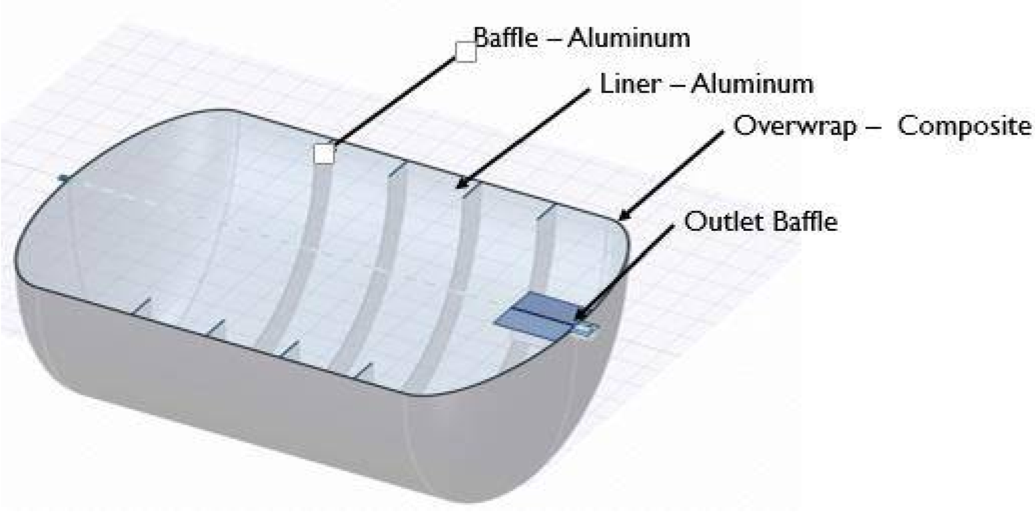

Figure 11 MON-25 Tank

The Helium tanks were also analyzed to ensure they can withstand the high pressure loads. The tanks are loaded on Earth at ambient conditions to 10,000 psi and can see higher pressures during heating on the launch pad.

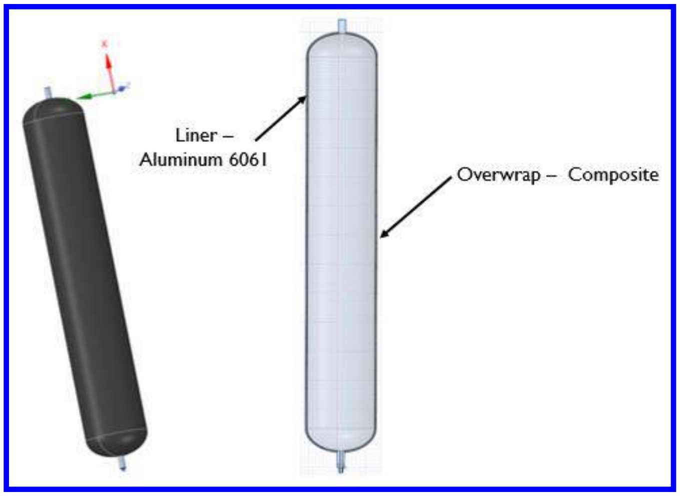

Figure 12 Helium Tanks

The motor case is titanium overwrapped with composite. It contains the fuels, injector, insulators and nozzle. Current planned launch temperature is -20C. If the motor was assembled at ambient temperatures, the high CTE of the SP7A would pull away from the case at low temperatures and likely break upon ignition due to lack of support. Installation of the SP7A grain into the titanium shell is at a lower temperature than -20C (for FT03 ~-21C and for FT04 ~-43C) resolves this issue. For the flight motor, being a single stage to orbit, flanges had to be designed out. After loading the fuels, insulators and other parts into the domes and cylinder section, those titanium pieces are to be welded together, overwrapped with composite and pressure tested after assembly. Analysis showed sufficient margin.

The propellant fabrication is still a work in progress, with some grains surviving the casting process and others not. Grains are post machined to the proper configuration (see Reference 7). This indicates there is still some level of residual stress in the grains, which still needs to be understood. The grains were analyzed against the thermal loads of the chilled press fit and the expected Martian extremes. Having done the chill fit, the grain remains mostly in compression for the cases analyzed.

For the vehicle structural components, the unsteady aerodynamics, loads and dynamics and structural assessment were completed. Aerodynamically, the loads are low and fairings typically required on Earth may be unnecessary. Wind tunnel testing could substantiate fairing removal, since there is not analogous test data. Entry, Decent and Landing into the Martian atmosphere impose unique loads. A Mars entry deceleration load of -15g is applied perpendicular to the thrust direction. Lander and vehicle stowed interfaces must efficiently handle these requirements to optimize overall lander and ascent mass and volume. No major load problems were apparent. There are ongoing discussions over the weights of some of the components.

E. Avionics

The avionics design of the hybrid MAV configuration was primarily focused on three major components: command and data handling, communications, and power. A number of high TRL off the shelf parts were available to provide necessary mission performance capability. Where necessary, custom avionics components were used. The avionics hardware architecture for this vehicle consisted of a flight computer, a power distribution board, and input/output board, an Inertial Measurement Unit (IMU), a star tracker, a radio transmitter, a radio transmitter, and batteries. The hardware layout and position of the avionics are shown below in Figure 13.

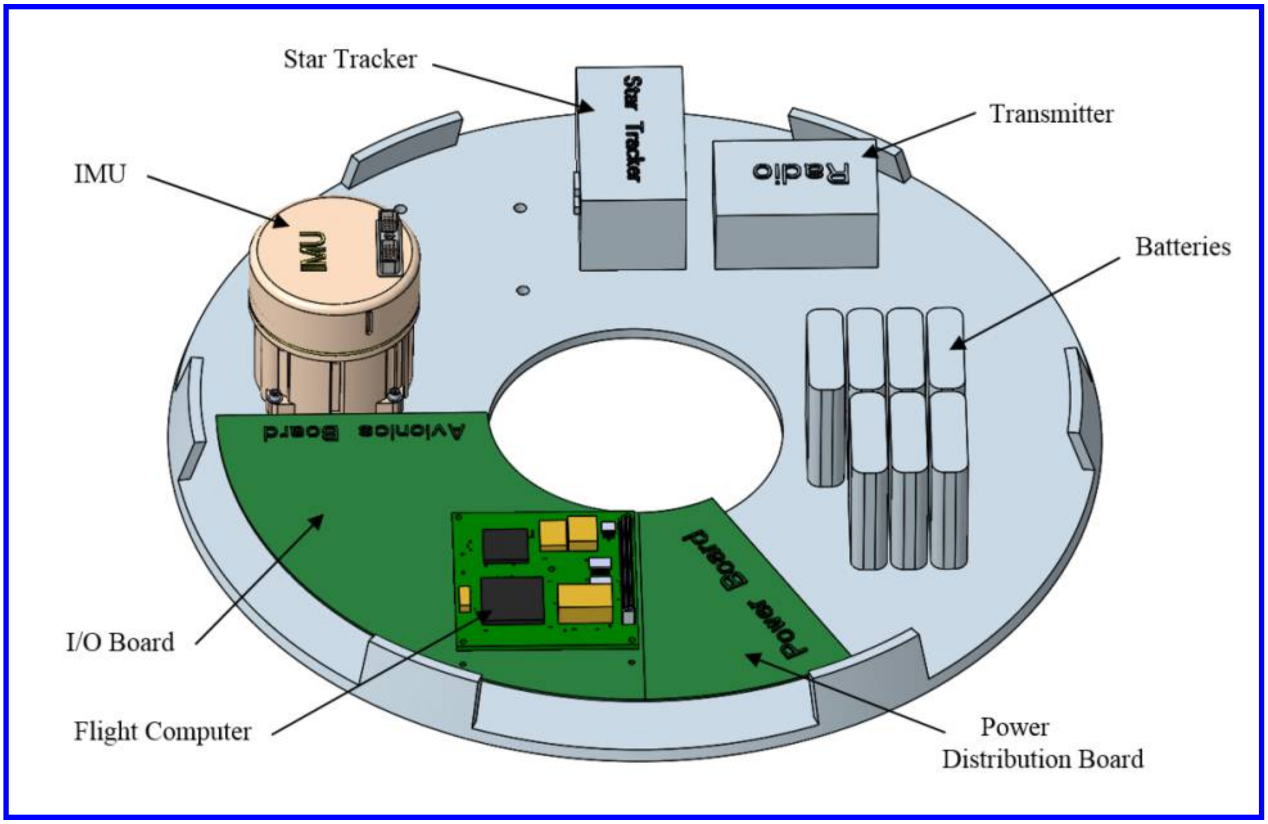

Figure 13 Avionics Location and Layout

Command and data handling of the vehicle during flight were upheld by the flight computer, star tracker, and IMU. These components ensure the correct positioning of the vehicle and allow for execution of GN&C algorithms through custom flight software. Communications for the vehicle are maintained through the use of a transmitter, antenna, and beacon to allow the vehicle to broadcast positioning data to the Mars Relay Network (MRN). Power storage and distribution was performed through a power distribution board and batteries. A significant amount of cabling was necessary to deliver power to thermal heaters throughout the vehicle.

The onboard flight computer in this study was known as the Sphinx. It was originally developed at NASA Jet Propulsion Laboratory (JPL) for use in similar missions and has been baselined for mass, power, and radiation tolerance. High level flight software would be developed in future analyses for use on this computer using the Core Flight System framework and the Real-Time Executive for Multiprocessor Systems operating system. This computer and software has significant challenges to overcome for the mission, in that it must ensure that launch commit criteria are met, provide IMU position data during navigation, provide active control of RCS/LITVC valves, transmit IMU telemetry to the MRN, identify and report any system fault conditions, and perform/confirm OS separation. Although the architecture for these functions has been outlined, it is beyond the scope of the PAA to actually develop it.

For position and navigational sensing, a small IMU with navigation-grade performance is assumed. This is necessary for achieving accurate attitude knowledge through gyrocompassing. Future studies will likely look at options to reduce vehicle performance requirements, which could potentially result in an even smaller IMU. A star tracker can be used to augment the capability of the IMU for further performance. The current GN&C design plans to only use the star tracker after leaving the Martian atmosphere.

The transmission of vital data such as position and vehicle states to the MRN would be provided by a transceiver. Although capable of receiving communication, the transmittal of data is all that is being considered at this time. This transceiver would be used in conjunction with either an omnidirectional wraparound or patch antenna. A beacon with an individual power supply will be placed on the vehicle as a means for the Earth Return Orbiter to capture the OS after orbital insertion. It is desired that the beacon remain operational on the spent MAV for up to 45 days post-injection.

While stowed prior to flight, power would be provided to the MAV by the SRL through an umbilical connection. During flight, however, onboard power would be needed to power avionics components, and RCS/LITVC valves. This power is assumed to be provided by lithium ion battery cells due to their ability to perform in cold temperatures, low loss during long storage periods, and recharge capability

F. GN&C

Both 3DOF and 6DOF trajectory analyses were completed for the hybrid MAV design. The assumed ascent plan is shown in Figure 14: burn to MECO target, coast to apoapsis, burn to circularize using a closed-loop, Powered Explicit Guidance (PEG) for both burns. This preliminary analysis made several simplifying assumptions. Additionally, events and situations that were not modeled include: motor shut down transient rates, body rate requirement for OS separation, possible attitude hold for a time prior to OS separation and Misalignments of RCS thrusters and off nominal performance. The GN&C analysis indicates the nominal Hybrid MAV closes with respect to orbit (300-375 km) with suitable attitude control. However, further work is required to determine how robust the solution is.

The GN&C analysis also recommended budgets for the RCS helium and LITVC MON-25. It was recommended that all the RCS thrusters, with the exception of the settling burn motors, be increased to the larger 6 N of thrust. To account for the missing analysis of the events, a factor of three was applied to the helium budget, was more than previously allocated in the MEL (input to the 6DOF design, indicating another iteration is required). The LITVC MON-25 budget was found to be sufficient at this point.

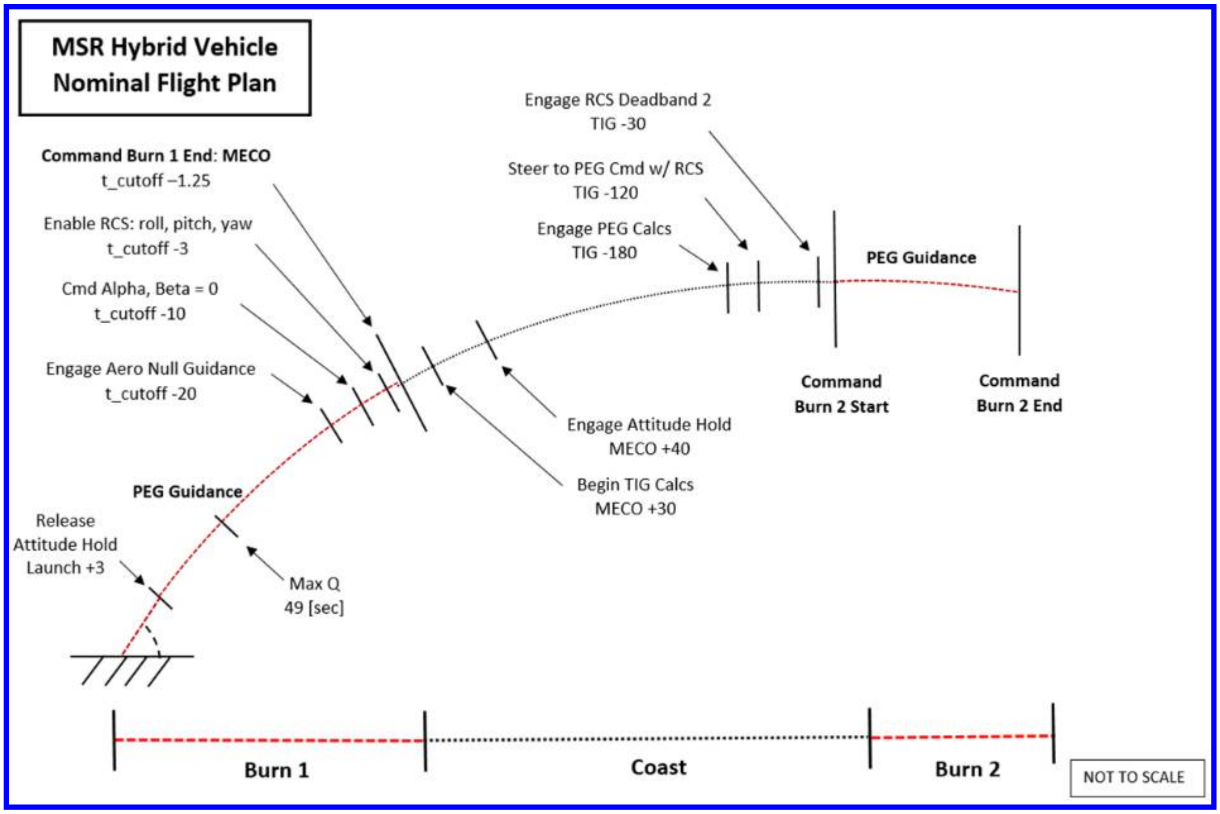

Figure 14 Hybrid Vehicle Flight Plan

G. Propulsion Options

There are several opportunities to improve the propulsion system design (mass reductions) that are being considered.

The hybrid pressurization system is currently oversized. Analysis of the blowdown system has indicated that with the helium gas at a lower temperature than what is currently planned for operation (-40C vs -20C), the system ends its life with approximately 3000 psi in the tanks. At the planned operational temperature (-20C), the end of life pressure is approximately 4000 psi. The operational pressure of the oxidizer system is nearly an order of magnitude lower than this. So, while some margin may be required to ensure the regulators operate properly, there is substantial room for improvement. Since all the helium system mass and residual helium is essentially payload, this could correspond to several kilograms of mass savings. Options for improvements include lowering the initial tank pressure, reducing the number of tanks, and possibly removing a feed system regulator. Beyond the conservativisms that exist in the design, there is potential for improvement in the helium system. There are multiple heaters planned to keep the various components warm on the Mars surface, and preferentially heating the helium tanks has been analyzed from a blow down perspective, which can drop the loaded helium mass substantially and possibly drop a regulator.

At the end of the hybrid second burn, there will be some residual helium in the helium tanks and the oxidizer tanks. If desired, the residual could be dumped thru the settling burn thrusters to provide a small finishing delta V to the orbit before jettisoning the samples in orbit.

The replacement of the ignition fluid with a hypergolic solid solution is being studied. That would eliminate an entire leg of the feed system, including one tank, residual MMH, helium pressurant, a solenoid valve, a fill and drain valve, 2 burst disks and one element of the motor injector. Simplification of the system (from a component count) will be traded against possible reductions in ISP due to the solid hypergolic additive.

The slosh baffle system design included in the CAD and MEL were the worst case (most massive) option since the 6DOF analysis has not been completed on the slosh loads. There is potential to optimize the design and reduce the mass.

The current 6DOF analysis has shown that the LITVC required for the ascent can be provided by four LITVC valves, not the eight currently listed in the MEL. While the mass of the individual valves is small, there is additional nozzle scarring and electric cables that could be removed. However, the 6DOF analysis does not include some of the launch scenarios currently being investigated. One includes mechanically tossing the MAV upwards and launching it before it hits the ground.

As the full-scale hybrid MAV test program matures, there is potential for mass reduction/performance increase within the hybrid motor itself. For example tests to date have indicated the C* efficiency is larger, briefly, than what is being used in the model. Improvements in C* efficiency would have a corresponding increase in ISP efficiency.

V. Plan Forward to Downselect

The PAA results will be out briefed in a peer review in mid-July of 2019. The expectation is that the results of the review will inform the propulsion system down select at the end of 2019.

A. Testing to Down Select

In the near term, there is ongoing testing occurring at SPG, WASP and Purdue. This will continue through FY19.

Two full-scale tests will be completed at Whittinghill Aerospace in the remainder of 2019. WASP’s FT04 grain/motor (Test B) was been assembled at MSFC at -43C and will be hot fired in July. This is the first large scale test with SP7A and MON-25. It will also focus on demonstrating a flight-like, rapid ignition. Motor B’s test results will drive FT05 (Test C), which is a slightly larger diameter motor to demonstrate the full duration burn (with restart) and the required total impulse to meet the mission.

SPG will be testing subscale motors to characterize the regression rate and structural integrity of SP7A. They will also be evaluating the structural integrity of the full-scale grains through rapid pressurization testing.

Purdue will complete fabrication of a subscale motor and test it under vacuum conditions. This motor will include the solid hypergolics they have been investigating over the past several years.

The high nozzle erosion still needs to be addressed. Sandpiper (a MON-25 hybrid) certification tests (see Reference 20), had low nozzle erosion, suggesting it will be achievable. The propulsion team continues to look at other nozzle materials and inlet conditions to the nozzle. This will be addressed in testing this year.

B. Vehicle to Down Select

Another design cycle will be completed after the PAA review. Inputs from the peer review will be incorporated, and the several design iterations will be completed.

C. Post Down Select

Assuming the MAV hybrid concept is selected, development work to mature the technology would continue on a rapid schedule. The vacuum test of the hybrid motor and LITVC function at White Sands Test Facility would need to be rescheduled. The primary goal of this testing is to validate the models being used to predict the LITVC performance. In addition to the LITVC validation, continued full scale testing will be necessary to refine understanding of the motor performance and optimize the design prior to entering a qualification program.

Purdue will continue to investigate the incorporation of solid hypergolics in SP7A, with a focus on how to make it functional in a larger, full scale motor. Removal of the hypergolic fuel tank and associated complexity would reduce the mass of the vehicle. However, the potential drawbacks of such a system (Isp decrease, etc.) will need to be traded against the benefits.

Plans for the out years include feed system component development, propulsion system modifications, and additional trades leading up to qualification.

A preliminary assessment of the qualification program necessary for this system is documented in Reference 21, wherein the number of component tests, qualification motors and the Earth-based flights are discussed.

VI. Conclusion

The MAV Hybrid concept has completed a Preliminary Architecture Assessment, reviewing all the major subsystems of the launch vehicle. No show stoppers were identified – the vehicle can be designed to fit in the allocated space, at roughly the allocated mass and tightly hit the required orbit for almost all cases examined. This design is an iterative process and it's expected that one or several more iterations will be required before it is complete. The next iteration is planned to directly follow the PAA in mid-July in time for a down select between the propulsion systems by the end of the year.

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The information presented about potential MSR is pre-decisional and is provided for planning and discussion purposes only. The decision to implement Mars Sample Return will not be finalized until NASA's completion of the National Environmental Policy Act (NEPA) process. Some of the research presented here was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

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