# A Single Stage to Orbi
# 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 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 ôs (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.

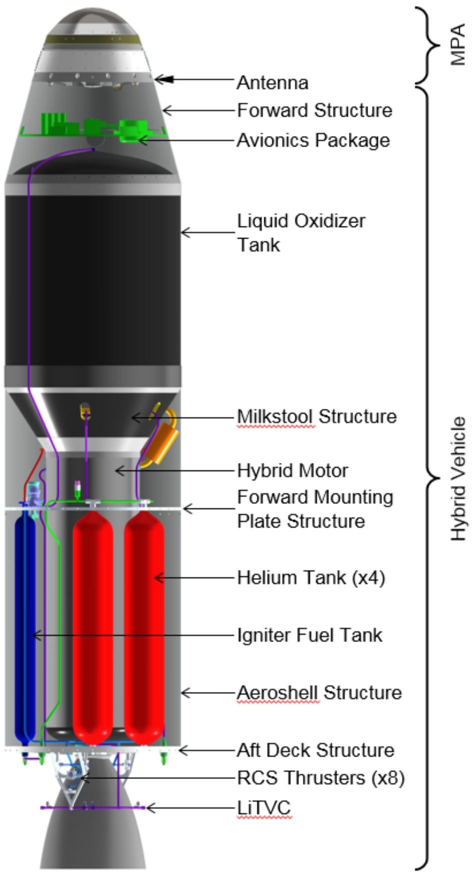


**Figure 3 MAV Hybrid Motor Concept**

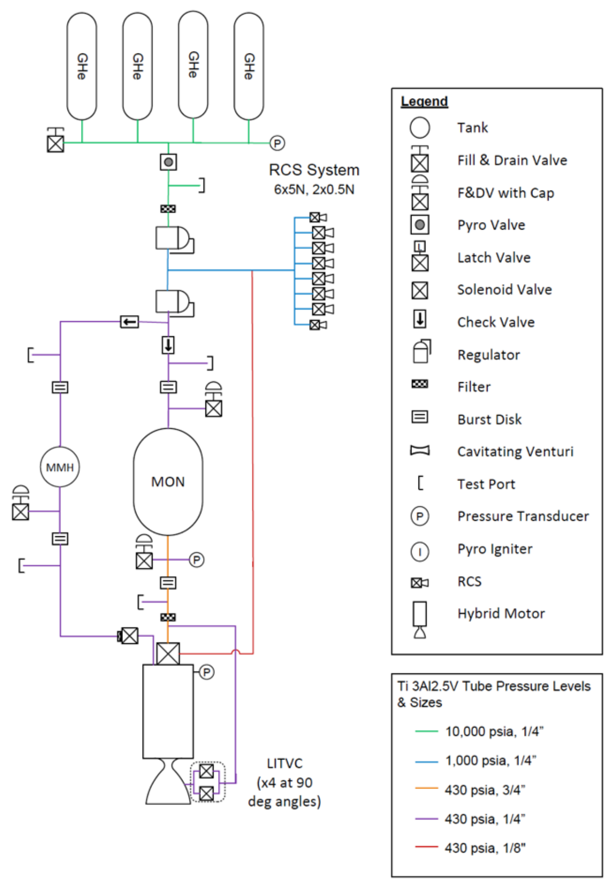


**Figure 4 MAV Hybrid Rocket System Schematic**

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.

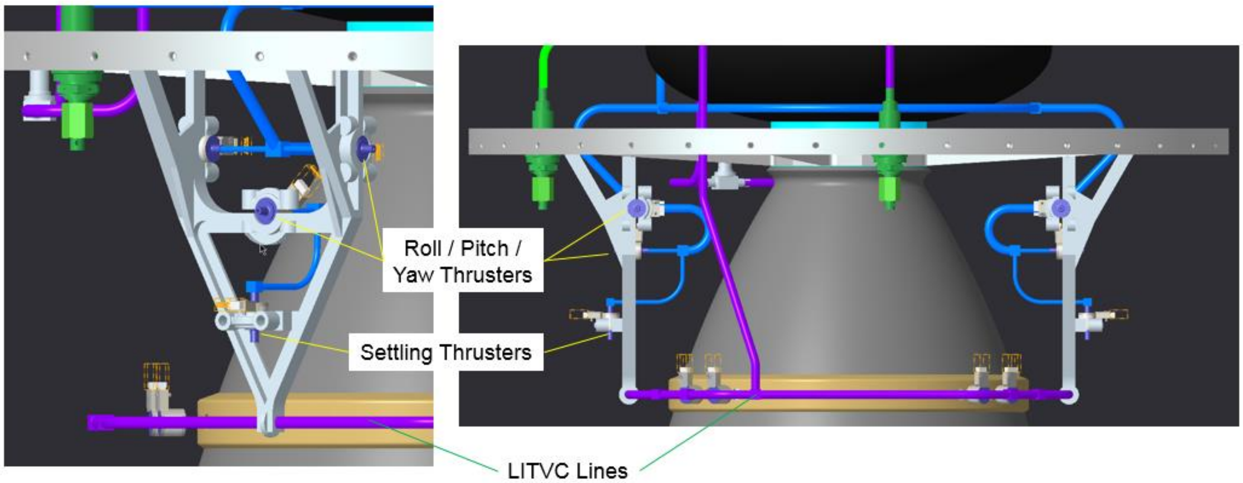


**Figure 5 RCS Configuration**

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.

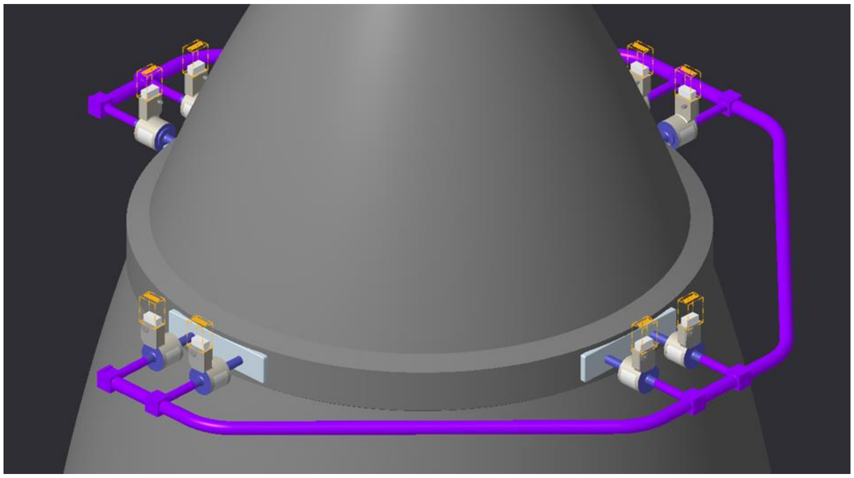

**Figure 6 LITVC Valves Supplied MON-25 Through Common Manifold**

### 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.

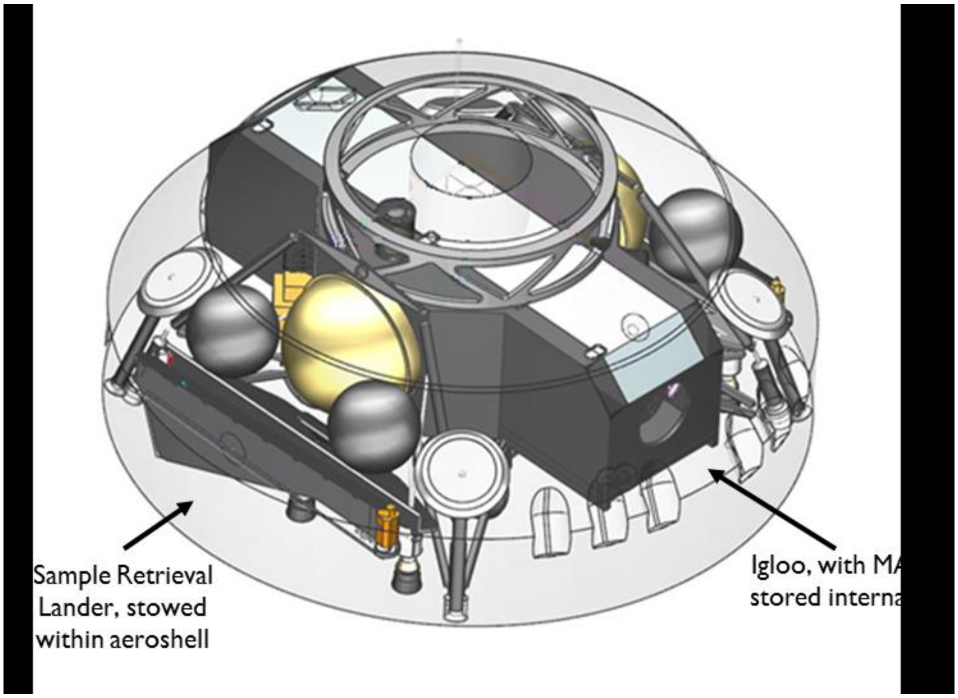


**Figure 7 MAV Stowed in Igloo on SRL**

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.

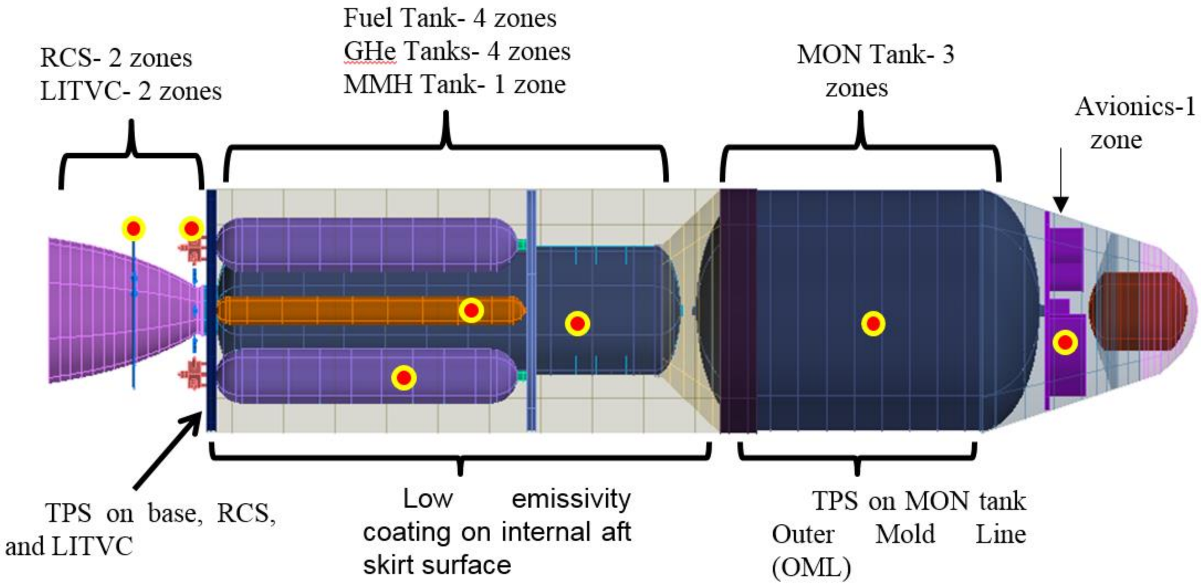


**Figure 9 Hybrid MAV Thermal Protection System (TPS) and Thermal Control System (TCS)**

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.

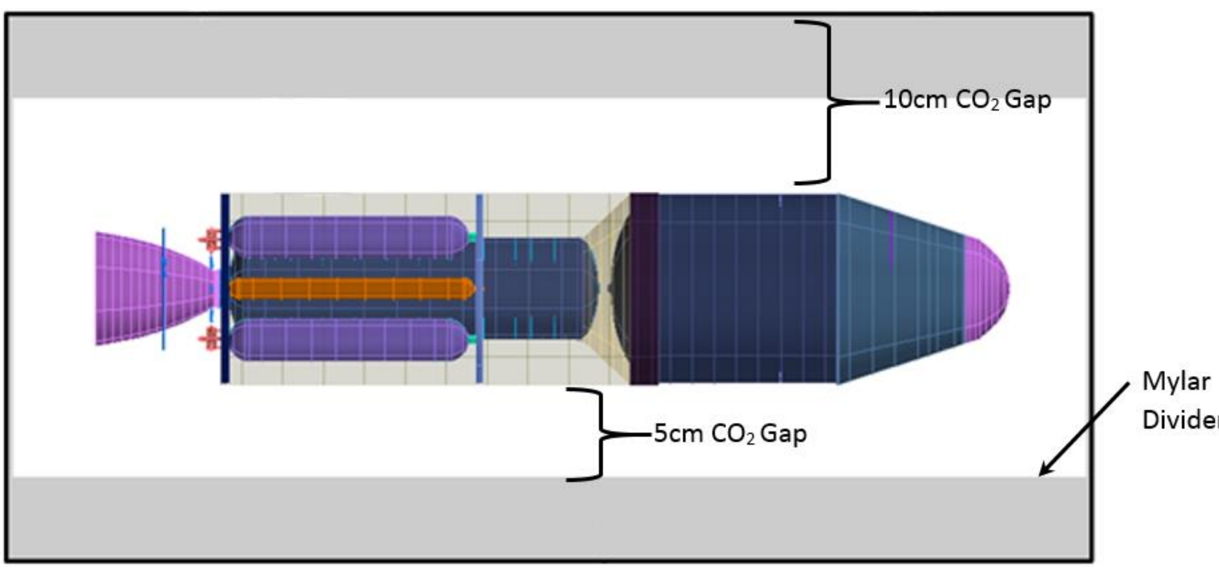


**Figure 10 MAV Within Igloo**

**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.

## 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 GHVLJQ LV DQ LWHUDWLYH SURFHVV DQG LW¶V H[SHFWHG WKDW RQH R
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 decisio Q WR LPSOHPHQW 0DUV 6DPSOH 5HWXUQ ZLOO QRW EH IL
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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