A Hybrid Mars Ascent Vehicle Concept for Low Temperature Storage and Operation

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A hybrid propulsion system presents many advantages for a potential Mars Ascent Vehicle including high specific impulse, restartability and predicted excellent low temperature survivability. This additional benefit of low temperature storage and operation could substantially reduce the power required to maintain the system while on Mars and therefore decrease the total landed system mass required for the system. A new wax-based hybrid fuel has been formulated to realize these low temperature benefits, while still preserving high performance (Isp). The freezing point of the oxidizer can be selected to match the capabilities of the fuel, in this case Mixed Oxides of Nitrogen has been selected. The main disadvantages of this system are associated with the relatively low technology readiness level of the selected hybrid propulsion system for operation on Mars. However, technology development efforts are currently underway to advance the hybrid propulsion system to a level where it could potentially compete with heritage propulsion systems. An internal study completed at JPL in 2015 identified the single stage to orbit hybrid MAV as the lowest gross liftoff mass case from a large range of potential propulsion systems. Updates to this design are presented here.

Nomenclature

CBE = Current Best Estimate
COPV = Composite Overwrap Pressure Vessel
DOF = Degree of Freedom
FY = Fiscal Year
GLOM = Gross Lift Off Mass
LITVC = Liquid Injection Thrust Vector Control
MAV = Mars Ascent Vehicle
MON = Mixed Oxides of Nitrogen, refers to N_2O_4 mixed with NO
MSR = Mars Sample Return
OS = Orbiting Sample
O/F = Oxidizer to Fuel Ratio
RCS = Reaction Control System
SSTO = Singe Stage to Orbit
TRL = Technology Readiness Level

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I. Introduction

A JPL led study evaluated a wide range of propulsion options for a Mars Ascent Vehicle (MAV) concept as part of a Mars Sample Return (MSR) effort. The potential MSR campaign is currently envisioned as three separate missions: one to collect and cache samples, a second to launch the samples from the surface of Mars into orbit around Mars and finally, a third mission to return the samples from orbit around Mars to Earth. This work focuses on the second part of this effort: lifting the samples from the surface of Mars to orbit around Mars. The samples are contained in the Orbiting Sample (OS) and are the main payload for the MAV.

The most recent MAV study began in Fiscal Year 2014 (FY14). At that time, ten permutations of solid, liquid bipropellant, monopropellant and hybrid propulsion systems were considered. These included two stage and single stage to orbit systems (with multiple starts). The second year of the study (FY15) refined the field to seven options, of which, the Single Stage to Orbit (SSTO) hybrid propulsion option resulted in the lowest Gross Lift Off Mass (GLOM) according to the study and will be the focus of this paper. Details of the complete JPL MAV study are captured in Ref. 1. Updates to the “baseline” subcase from the FY15 designs are presented.

The selection of the hybrid as the baseline for this study has allowed GN&C to focus on the unique requirements of the hybrid trajectory. These results have been incorporated in the latest system update. Minor improvements in the hybrid model have also been made. A new wax-based hybrid fuel formulation was developed for the MAV in order to withstand the harsh and variable Mars environment with only a minimal layer of passive insulation and with substantial energy savings for a notional lander. Thermal cycling of the fuel has determined that it can survive temperature extremes expected on Mars. A complete preliminary design using this new fuel formulation in combination with a low temperature oxidizer: Mixed Oxides of Nitrogen (MON30) is presented. Potential challenges along a path towards developing such a system are discussed. As are the strides made in technology maturation over the past year.

II. FY2015 Design and Study Variables

A. FY2015 Study Variables

The 2015 study investigated solid, liquid and hybrid propulsion options using a parametric approach with six subcases [Ref. 1]. Of these options, the hybrid design looked the most promising, therefore only the hybrid propulsion subcases will be discussed here. The 2015 hybrid design MAV held several variables constant for each of the subcases (see Table 1). Not all of these variables were optimized due to the number of cases being considered at that point in the study: seven propulsion systems, each with six subcases for a total of 42 different designs. The overall hybrid model was improved in FY2016 and will be discussed in the next section. Mass margins are applied to the MAV using the AIAA S-120 Standard [Ref. 2].

Table 1: Constant Hybrid Design Variables. *The variables presented here were not changed between the subcases.*

	Value
Fuel/Oxidizer	SP7/MON30
Oxidizer to Fuel Ratio	4.56
Isp (assumes 95% efficiency, Ref. 3)	317 s
Chamber Pressure	250 psia
Reaction Control System (RCS)	N_2 Cold Gas (8 thrusters)
Nozzle Area Ratio	40
Thrust Vector Control (TVC)	Liquid Injection TVC

Each of subcases had a different dry mass allocation for telecommunications, avionics and a notional Orbiting Sample (OS). The total dry mass (payload plus non-prop dry mass) spanned a range of 27.15 kg up to 56.9 kg. The six different subcases are presented in Table 2. This presents a parametric view of how the system masses change with increasing dry mass or payload mass. This study was intended to capture the range of payload masses for the MAV system and discover the sensitivities of each propulsion system.

B. FY2015 Design

It is important to discuss the original design, since the new design builds upon this one. The hybrid MAV design from FY15 utilizes a newly developed wax-based fuel: SP7 [Ref. 4] and MON30, Mixed Oxides of Nitrogen with 30 percent NO, has been chosen as the oxidizer. The low temperature capability of this oxidizer allows the MAV to take advantage of the low temperature performance of the fuel by not having to thermally isolate one from the other. The minimum allowable flight temperature of MON decreases with increasing NO content. MON30 has an allowable flight temperature of about -71C. It is space storable and can survive the high temperatures that may occur during launch from Earth. MON30 has not been used as extensively as MON25; however, the substantial decrease in allowable flight temperature drives the choice in this case.

Table 2: Results for the FY15 Case 7, Regulated Hybrid MAV Concept

		Subcase (Based on Payload and Non-Prop Dry Mass Allocation)					
Subcase:		1	2	3	4	5	6
Payload mass (OS):	kg	6.65	9	14	14	17	20
GLOM:	kg	171.4	187.3	219.1	257.3	283.6	300
Total Mass	kg	164.3	177.9	204.6	242.8	266.1	279.5
Propellant Mass	kg	122.8	134	156.3	183	202.3	214.3
Prop Dry Mass	kg	21.0	21.9	23.6	25.8	27.3	28.3
Non-Prop Dry Mass	kg	20.5	22.0	24.6	34.0	36.5	36.9
RCS Mass	kg	2.02	2.02	2.02	2.02	2.02	2.02
Thrust	N	4885	5150	5679	6312	6768	7053
Stack height:	m	2.6	2.6	2.9	3.1	3.3	3.4
Hybrid Motor Outer Diameter	cm	18.35	18.8	19.69	20.76	21.53	22.01

The O/F ratio was calculated using Chemical Equilibrium with Applications (CEA) [Ref. 5]. However, testing should determine the final design point and may need to account for a small O/F shift depending on the regression rate exponent, which has not yet been determined for this propellant combination. The specific impulse assumes 95% efficiency (including both the combustion and nozzle efficiencies). This design uses pressure fed system with high pressure gaseous helium.

The relatively high regression rate fuel enables the hybrid to be designed with a single, cylindrical port in the fuel grain. The fuel grain ~~utilizes a 3 to 1 outer to inner diameter ratio to~~ has a moderately high volumetric loading ~~maximize packaging~~ without over stressing the fuel. The regression rate of the SP7 fuel is about 60-70% that of neat paraffin [Ref. 4]. Decreased thrust is actually desirable for this application to reduce dynamic pressure loads at the end of the first burn and consequentially decrease the requirements on the reaction control system (RCS). Additionally, the new fuel has a wider temperature range capability than pure paraffin [Ref. 6]. This baseline SSTO design takes advantage of the hybrid's ability to shutdown and restart.

The Case 7.3 is taken as the baseline for the hybrid cases and the 2015 iteration is shown in Figure 1. Most of the ΔV (nearly 80%) would be imparted during the first burn, which is about 76 seconds long. After a little more than a 12-minute coast, a short second burn of about 10 seconds would be used to circularize the orbit in a near Hohmann transfer. The GLOM of this point design

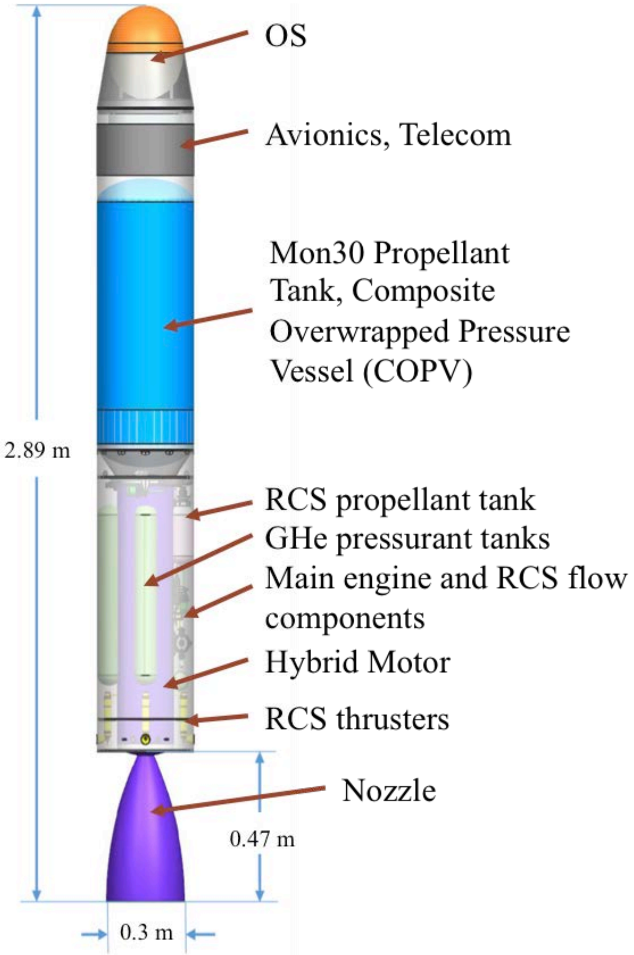

Figure 1. Hybrid MAV Case 7.3. *The result for the hybrid propulsion system for the FY2015 study.*

is 219 kg with a total system length of 2.89 m. The OS is shown at the top of Figure 1 and is also the nosecone of the MAV. It will be thermally protected from the dynamic heating loads experienced during launch. The avionics, telecom and command and data handling reside in the compartment between the OS and the oxidizer tank. The MON30 oxidizer is contained within a 38.1 cm outer diameter composite overwrap pressure vessel (COPV). The hybrid motor is at the aft end of the MAV, as expected. Since the motor's size is dictated by its ballistics, the additional space around the motor is used to house the COPV pressurant and gaseous nitrogen RCS tanks as well as the feed system components and the RCS thrusters.

The chamber pressure was selected, but not optimized, to be 250 psia. Unlike solid rockets, the fuel regression rate in a hybrid rocket is not a strong function of chamber pressure. Therefore, hybrids have the design flexibility to optimize chamber pressure with regard to overall system design. From a propellant combination standpoint, the only issue is to ensure that the chamber pressure stays above the supercritical pressure of the fuel. SP7 will have a lower supercritical pressure than that of paraffin, which is 97 psi [Ref. 7]. The biggest influence of the selected chamber pressure will be the nozzle size and pressurant mass. Higher chamber pressure enables a shorter and less massive nozzle for the same area ratio. However, it will require more pressurant to deliver the oxidizer. The combustion chamber mass will not influence this trade since the minimum wall thickness of a titanium combustion chamber (0.022 inch or 0.56 mm) has capability to withstand nearly 800 psi.

A cold gas Reaction Control System (RCS) uses a separate gaseous N_2 tank. The dynamic pressure loading at the end of the first burn and coast period is the current driver for the RCS requirement. The eight thrusters (four at 22 N and four at 5 N) would be located at the aft end of the combustion chamber, maximizing the moment arm and utilizing otherwise empty space around the motor. The trajectory is still being determined and there is potential to decrease the number of thrusters required to six, based on the results of a higher fidelity (6 degree of freedom (DOF) instead of 3 DOF) simulation. A constant RCS mass is used across all the subcases until the final simulations are complete. Using a separate GN_2 RCS sub-system produced the minimum GLOM in our study. This was traded against a dual use He RCS/pressurization system (utilizing a common tank). Alternative RCS systems were also considered including hydrazine thrusters, but were all found to be more massive.

The thrust of the hybrid propulsion system is allowed to increase with the propellant mass to ensure a minimum oxidizer mass flux (mass flow rate of oxidizer divided by the port area) at the end of the burn. This is one variable that the other propulsion systems were not allowed to adjust during the study. The solid and liquid systems had set thrust levels regardless of the subcase. Increasing thrust with propellant mass actually hurts the hybrid design because it leads to a higher dynamic pressure at burn out. This dynamic pressure was one of the optimization goals for the trajectory simulation, so the varying thrust made this goal more difficult to achieve. Even with this disadvantage, the hybrid design was still the most favorable. Further testing with the proposed propellant combination could alleviate this constraint.

The results of the parametric study are presented in Table 2. While Table 2 is not representative of a final design, it is very useful to see how the mass, size and related parameters of a hybrid Mars Ascent Vehicle could change with increasing requirements in payload, avionics, telecom, etc. This data was used originally to compare the hybrid system to the other propulsion options to determine the best option for this application.

III. Updated Hybrid Design

The hybrid design has matured since the FY15 study's completion; however, the overall system remains quite similar. Case 7.3 was taken to be the baseline and is the case presented here. Since only one case was evaluated this year (as opposed to 42) a much more detailed model was completed. Wherever possible, updates to the design were applied to capture more detail in the model. The case (7.3) determined the redundancy approach and requirement for the avionics, telecom, and harness, which remains unchanged. In this case, they total 11.31 kg. The OS is taken to be 14 kg, a substantial increase since past studies.

A. Updated Design

The updated design is presented in Table 3~~ and an overview of the system is given in Figure 2~~. The GLOM has increased due to more demanding requirements on the system. The design and requirement changes will be identified and discussed in the following section. The thrust level has remained relatively constant despite the increased GLOM due to a decrease in the minimum allowable oxidizer mass flux~~ (4 g/cm^{2}s)~~. Residual propellant was taken into account and is bookkept in the loaded propellant masses below~~ (4.1 kg)~~.

Table 3: Updated Regulated Hybrid MAV Concept

Updated FY2016 Design	Units	Value
Payload mass (OS):	kg	14
GLOM	kg	229
Propulsion Dry Mass (includes RCS dry mass)	kg	23.1
Non-Propulsion Dry Mass	kg	19.99
Loaded Fuel Mass	kg	30.6
Loaded Oxidizer Mass (includes MON for LITVC)	kg	139.4
Pressurant and RCS propellant mass	kg	1.62
Thrust	N	5430
Specific Impulse (Isp)	s	320
O/F Ratio	-	4.56
Total ΔV	m/s	3944
Total Burn Time	s	93.4
Stack height	m	2.9
Hybrid Motor Outer Diameter	cm	23.6

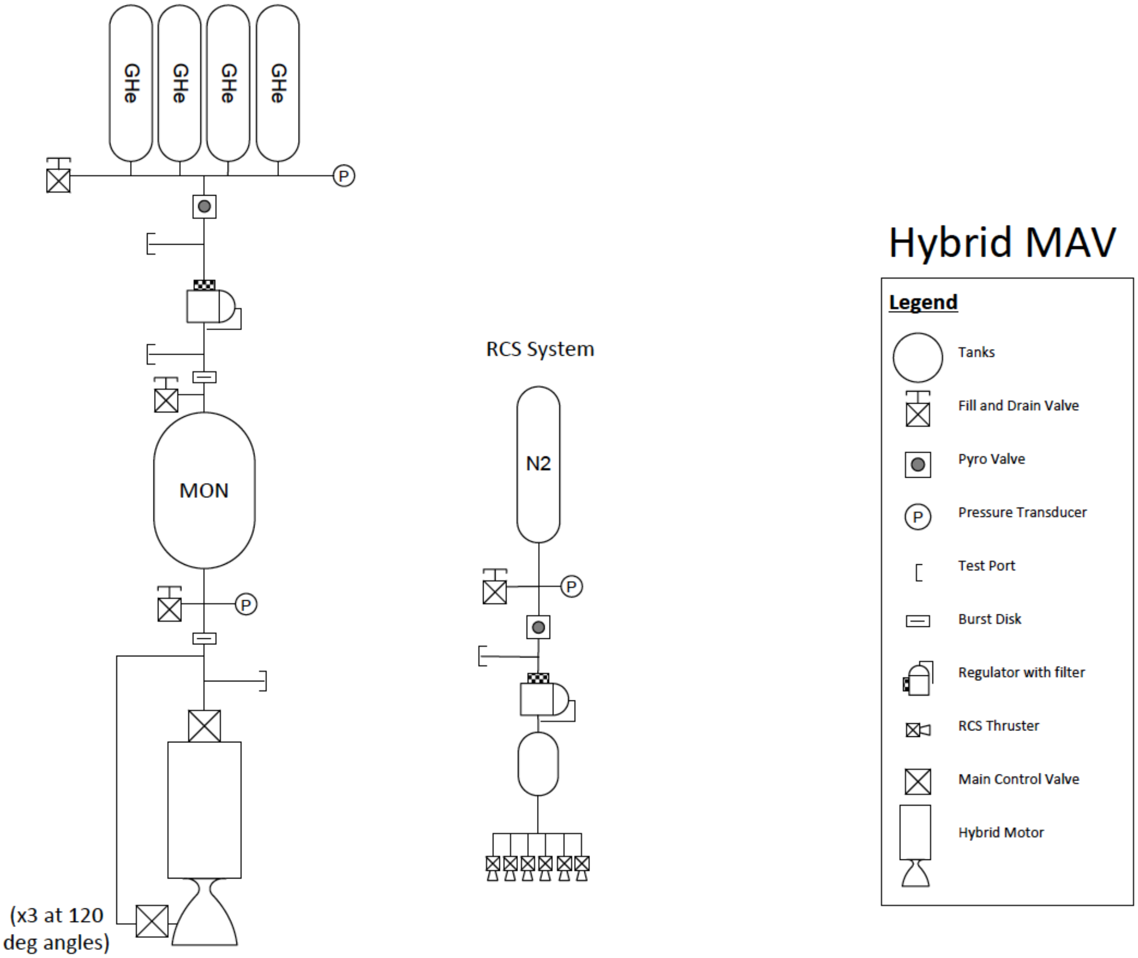

Figure 2. Potential Hybrid Rocket MAV Design. *A design for a potential hybrid Mars Ascent Vehicle with a separate RCS system.*

B. Changes from the FY2015 Design

The hybrid MAV design presented in this section updates the 2015 design by improving the robustness of the system through knowledge gained in the last year as well as by replacing several components with better or lighter mass designs.

Figure 2~~3~~ shows the updated design. The OS is still the nose of the MAV. The OS skirt is undergoing substantial design changes as the best method to load the samples is currently being investigated. The shortest length option is shown here making the total MAV length 2.9 meters. The EDL system is imposing a length constraint of 3 meters on the MAV. Therefore, the OS skirt and sample loading system is considered a major risk to the system length requirement. The avionics compartment us unchanged from the 2015 design. The oxidizer tank has grown slightly to accommodated an increased propellant load.

The GN&C requirements have updated since the 2015 design leading to a substantial increase in gaseous nitrogen for RCS. There are now six tanks around combustion chamber for the pressurization and reaction control systems, including a small accumulator. The RCS tank and four Helium tanks were updated to be same diameter. This allows for ease of packaging as well as a cost reduction from a common qualification program.

The propulsion system components are also housed around the exterior of the motor. The fill and drain valve has been replaced by a lighter mass option saving more than 100 grams per unit in the Current Best Estimate (CBE) mass. The mass model for the tubing was updated to reflect more accurate run lengths based on the geometry of the system.

Several update were mad to the motor itself. The combustion chamber is still targeting 250 psi, awaiting a complete system optimization. The insulation mass for the section of the motor typically protected by fuel has been decreased to withstand ~~10~~ several seconds of burning. It was originally based on a fraction of the exposed insulator, which led to an over estimate in mass for the FY2015. The aft end of the motor was expanded by adding a convergent section after the post combustion chamber. Finally, the nozzle length was decreased slightly, representing a more aggressive, but feasible bell design. While all these changes were fairly minor, they resulted in a substantial increase in GLOM, about 10 kg. However, the hybrid MAV has managed to stay within the 3 m length constraint currently applied to the system.

IV. Areas of Technology Development

The hybrid design is the lowest GLOM option; however, it is also at the lowest technology readiness level (TRL) of any of the options. This is a substantial challenge because technologies need to be developed to TRL 6 before they can be infused into a flight system. Technology development tasks are currently underway with the goal of making this technology mature enough to be adopted for a mission in the mid- to late 2020's.

Wherever feasible, current and previous hybrid systems have been leveraged for information. A paraffin/N_2O hybrid propelled sounding rocket, Peregrine, is being developed to for a flight test [Ref. 3]. This sounding rocket will be used as a path finder for several systems that could be used for a MAV or MAV Earth launched demonstrator. The MAV demonstrator would have different oxidizers and fuels, but will still require fins, nose cones, etc. that could be based on the Peregrine design.

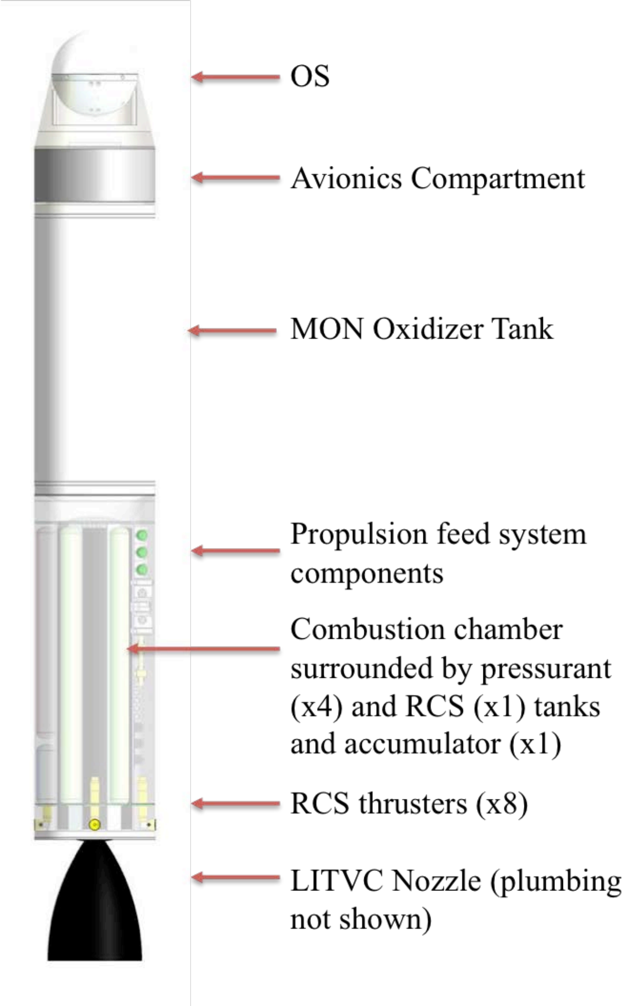

Figure 2~~3~~. Updated Design for a Hybrid MAV.

Another hybrid design being used to inform the present MAV work was the target missile: Sandpiper. It was certified for flight in the 1960s [Ref. 8]. Sandpiper used a Plexiglas motor with 10% magnesium and MON25 as the oxidizer. The oxidizer was pressurized by a blow down system, similar to the design presented here. Some of the parts could be used in the MAV application; however the differences in the technology, environment and use location indicate that substantial developments will still be required.

A. New Propellant Combination

The design leverages a new propellant combination: one that had not been tested before this MAV driven technology development program. Space Propulsion Group, Inc. developed a wax-based fuel formulation that has performance similar to paraffin-wax, but with a lower regressing rate and that can survive over a wider range of temperatures. The fuel has been shown to have a regression rate of approximately 60-70% that of paraffin with N_2O.

Preliminary thermal cycling of the fuel in a single port configuration was carried out at JPL last summer and determined that the fuel could withstand the expected thermal gradients over a few cycles. Longer term thermal cycling (201 cycles) of the fuel in a representative size and configuration has been in progress at NASA Marshall Space Flight Center [Ref. 6] and will be completed in the summer of 2016.

1. *Ground Testing*

The propellant combination selected for the MAV design presented here has not yet been tested. SP7 was tested with N_2O at SPG's Butte, MT facility to confirm capabilities with a non-toxic oxidizer. This testing was done on a subscale motor. The regression rate was also checked with the grains conditioned to -20C, with little/no change in the measured regression rate. This is in agreement with the understanding of hybrid combustion where the heat penetration into the grain depth is minimal. Purdue University has completed preliminary testing of SP7 with MON3 in their Optical Combustion Chamber, which burns a cylinder of fuel in a quartz combustion chamber. This particular combustion chamber flows the oxidizer on the exterior of the fuel, allowing visual access to the combustion. Purdue has also completed several tests of paraffin (and additives) with MON3 and MON25. However, have not yet achieved steady combustion without additives to the fuel or oxidizer.

Subcontracts are currently underway with Parabilis Space Technologies, Inc. and Space Propulsion Group, Inc. to complete ground testing of SP7 with MON3 oxidizer in sub and full-scale configurations. Data from these tests is expected at the end of the summer of 2016. Two major outputs of this effort are anticipated. First, confirmation that the propellant combination can be ignited and combusted reasonably well (a completely stable motor is not required during this short period of time; however a path towards achieving stability should be feasible.) Second, regression rate data on this new propellant combination. Current design efforts have assumed empirical combustion constants for SP7 with N_2O, using data from SPG's preliminary testing. While some hybrids have been shown to scale predictably [Ref. 9], there is a hypothesis that the regression rate will decrease at a larger port size with the same oxidizer flux [Ref. 10]. This testing will provide data at different sizes to test that hypothesis.

B. Hypergolic Ignition

A single stage to orbit Mars Ascent Vehicle relies on reignition, requiring a minimum of two burns for orbit insertion. The optimized trajectory used in this study was similar to a Hohmann transfer, with one main burn providing approximately 80% of the ΔV, a coast period and then a second burn to inject into Mars orbit. Additional burns may become desirable to clean up the final orbit, ensure sufficient separation between the MAV and OS after release, or deorbit the MAV after completing its mission. Propellant mass for these burns is not included in the design presented here. However, ignition techniques enabling 3-5 burns are currently being explored to determine the feasibility of additional restarts.

Current hybrid rockets typically employ single use, small solid propellant igniters, see Ref. 3. It is possible to utilize multiple solid propellant igniters for multiple restarts. However, the unused igniters need to be protected for all previous burns. Solid igniters would limit the temperature range for the MAV, so alternative approaches are strongly desired.

1. *Hypergolic testing*

Hypergolic ignition was identified by the FY2015 study as being the most promising option to complete the required multiple starts [Ref. 11]. Therefore, solid additives to the fuel are currently being investigated in attempt to determine a hypergolic combination with MON. This research is being conducted at Purdue and Penn State Universities. First, solid additives are being tested directly with MON to determine reactivity and ignition delays. The most promising candidates will be mixed with SP7 to understand the affects that the fuel may have on the additives. The main concern is that the wax-based fuel will inhibit the hypergolic reaction.

C. Thrust Vector Control

Thrust Vector Control (TVC) will be utilized to help control the eventual Mars Ascent Vehicle. There are multiple options for thrust vector control; however, Liquid Injection Thrust Vector Control (LITVC) is the current frontrunner for the hybrid design. In LITVC, a liquid is injected in the supersonic section of the nozzle, which creates an oblique shock. This shock deflects the thrust by up to about 5°. TVC capability of ±5° is sufficient for the planned launch from the Martian surface through orbit injection. Preliminary, conservative analysis suggests that about 2 kg of oxidizer would be necessary to complete the TVC required by a hybrid MAV using LITVC. This additional propellant as well as associated valves, tubing, etc. have already been added to the design presented here. The oxidizer used for LITVC does increase the thrust of the motor slightly and does contribute to the motor total impulse with a slightly lower ISP then the oxidizer consumed in the motor.

Ongoing research at NASA MSFC is focusing on the design of the LITVC system. An additional inlet for the LITVC system is currently being considered. Further analysis and potentially testing will determine if 3 or 4 are required to meet the guidance requirements.

D. Pump Trade

An electric pump could be considered for the hybrid MAV. The GLOM could be decreased by 10 kg (back to the FY2015 result level) if conventional batteries are used and 15 kg if new battery technology (250 W/kg) could be used. This new battery technology as not yet been tested in space applications; therefore it would require qualification. The pump is an interesting tuning knob, because it could be used as a means to decreasing overall length instead of GLOM if that becomes the driving constraint.

In a pumped hybrid case, it is beneficial to use gaseous nitrogen for both the pressurant and the RCS system. The regulation is broken up into a two stage system substantially decreasing the requirements on the regulator. This design reduced the number of tanks required for pressurant and RCS from five (four He pressurant tanks and one N_2 tank) down to two N_2 tanks. The pump pressure not only feeds the oxidizer into the combustion chamber, but also to the LITVC ports.

Having a single pressurant/RCS source allows all the residual GN_2 and MON to be used for a final OS avoidance maneuver if desired. ~~It should be determined if the residuals carry enough impulse to complete this. Venting all the gas would deliver approximately 450 N-sec.~~The residuals could be used towards this application. The desired impulse will need to be determined. Like many of the technologies being considered for the hybrid MAV, the pump is at a relatively low TRL. In this case, it has been tested with a non-toxic, referee fluid, however, it has not yet been tested with MON.

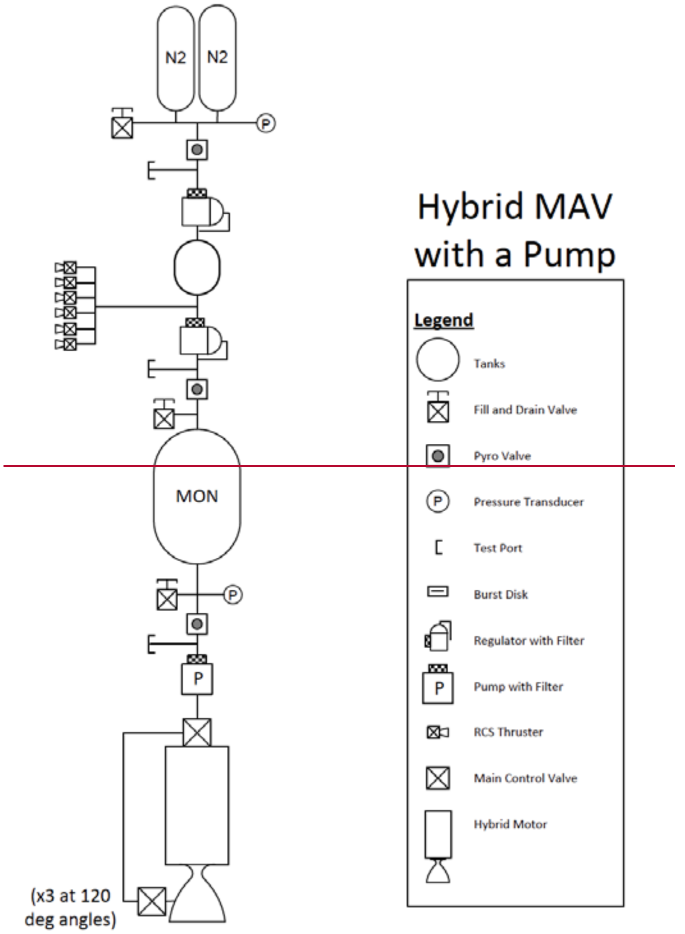

Figure 1. Notional Hybrid Rocket MAV Design Using a Pump. *The pump allows the system to become dual use with the N_2 pressurant being used directly for the RCS system.*

Since the fuel regression rate is dependent on the oxidizer mass flux, hybrid motors can be throttled by just tuning the oxidizer flow. Therefore, the pump could be used to throttle the oxidizer flow, and therefore the thrust. This could be a significant advantage for the MAV control system. Trajectory analysis is not currently allowing the motor to throttle, so these benefits have not yet been realized.

V. Path Forward

A. Earth-based MAV Demo

The technologies presented here are very promising for a Mars Ascent Vehicle. However, it can be seen that the hybrid propulsion system and MAV system are at relatively low TRL. In order to prepare for potential infusion into a Mars mission, an Earth-based flight of a representative hybrid MAV is currently in the planning stages. Peregrine is being used as a pathfinder in this area. Not all flight parameters can be matched in an Earth-based launch; however, this will enable testing of the entire MAV system. Confidence gained from testing a complex hybrid system design, like the one presented here could be the turning point for infusion of this technology. While not yet finalized, the goal would be to complete a Earth-based flight test of a MAV-like design by the end of the decade.

B. Optimize System Variables

Several trades have been completed at this point; however a complete multidiscipline optimization has not been completed. Variables in the propulsion system to be optimized include diameter, MAV length, oxidizer mass flux, chamber pressure, tank pressure, thrust, nozzle length and expansion ratio. A Genetic Algorithm previously used for hybrid motor boosters [Ref. 12] is being modified for the MAV configuration. The function to optimize will more than likely be gross lift off mass. Genetic algorithm results will be compared to the baseline vehicle to validate/confirm assumptions in the design space.

VI. Conclusion

A viable design for a potential hybrid Mars Ascent Vehicle has been presented with a GLOM of 229 kg and system length of 2.9 m. This detailed design represents increased understanding of the MAV over 2.5 years of study, including individual component selection. However, has not been completely optimized and further refinement is anticipated. The hybrid MAV is very promising because of its high performance, ability to restart and storability under Mars ambient conditions. A trade study indicated that adding an electric pump could further reduce the GLOM of the hybrid system, especially if new battery technology is adopted.

Great strides in technology development are being made for a hybrid MAV through testing a new propellant combination and studying potential hypergolic additives. Ground testing of the SP7/MON propellant combination could enable a new, low temperature, high performance option for not just a Mars Ascent vehicle, but for other in-space propulsion applications. Testing of potential hypergolic additives to the solid fuel is currently underway and could dramatically simplify the ignition system for the hybrid MAV. The excellent potential performance of the hybrid MAV is driving technology development instead of relying on heritage.

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