

# MARS ASCENT VEHICLE HYBRID PROPULSION DEVELOPMENT

G.T. Story

ER52, Solid Propulsion Branch  
National Aeronautics and Space Administration  
Marshall Space Flight Center, AL

A.C. Karp, B. Nakazono

Jet Propulsion Laboratory, California Institute of Technology  
Pasadena, CA

G. Whittinghill

Whittinghill Aerospace LLC  
Camarillo, CA

G.G. Zilliac

NASA Ames Research Center  
Moffett Field, Mountain View, CA

## Abstract

Hybrid propulsion is being investigated as a propulsion method for a possible Mars Ascent Vehicle (MAV) application. MAV is part of a proposed larger Mars Sample Return (MSR) campaign plan to bring samples from Mars to earth for examination. The Mars Ascent Vehicle would launch Mars surface samples found and packaged by the Mars 2020 mission to orbit around Mars. This version of hybrid propulsion is based on a wax based solid fuel, called SP7A, and a Mixed Oxides of Nitrogen oxidizer, MON-25. SP7 is a new fuel formulation developed by Space Propulsion Group and was modified for this application to be resistant to Mars temperature extremes and modified again to lower the regression rate to become SP7A. MON-25 was chosen for its low freezing temperature. Due to cost constraints, MON-3 was the oxidizer used during testing through 2018. In 2019, full scale hybrid testing with MON-25 commenced in Mojave, CA by Whittinghill Aerospace. One flight motor will be subjected to thermal cycling in a vacuum and later fired in a vacuum to demonstrate the proposed Liquid Injection Thrust Vector Control system performance at White Sands Test Facility (WSTF). In addition, there will be MON-25 characterization work done at Purdue University and WSTF. Additional testing of subscale and full scale motors will be conducted with MON-3 with fuel grain stress, fuel grain support and case design test objectives by Space Propulsion Group Inc. of Butte, MT. This paper documents some of the testing, issues and accomplishments with the MAV hybrid propulsion option that is being considered (along with a two-stage solid propulsion option).

## 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 samples from various locations and leave them on the Martian surface. The Mars Ascent Vehicle is a proposed mission to be launched in the Sample Retrieval Lander (SRL). A Sample Fetch Rover, which will leave the SRL, will pick up the prepackaged rock 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 the OS into an orbit around Mars. An Earth Return Orbiter, also

proposed, would retrieve the OS from orbit and bring it back to Earth. For further details on the larger program, see reference 1.

Over the last two decades there have been many studies and development efforts for a Mars Ascent Vehicle. These studies included solids, bi-prop liquids, spinning solids, gelled propellants, monoprops, 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.

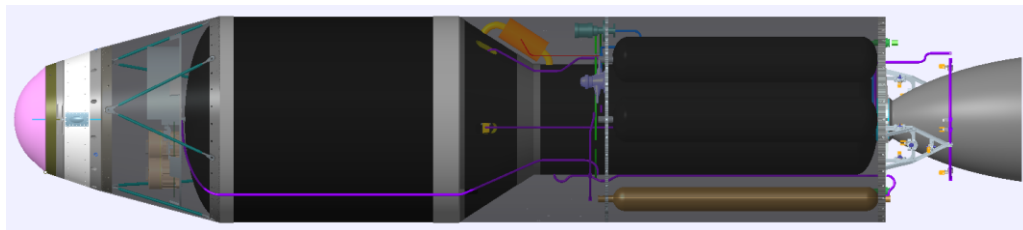
Further investigation in that trade suggested that a single stage to orbit hybrid rocket vehicle that is capable of a restart could be advantageous in the MAV role. Low temperature capabilities, higher Specific Impulse and no need for staging were potential benefits over other systems. However, this system had a lower Technology Readiness Level than the other concepts. Since the launch was proposed to be more a decade away, there was time to develop the technology in the interim. The goal of this effort was to raise the TRL to a level 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 MAVRIC. Reference 3 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 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 4. That study led to a larger vehicle study between a two stage to orbit solid and the single stage 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 efforts 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. Whittinghill Aerospace (WASP), Space Propulsion Group (SPG), and Purdue University have all contributed to the effort.

## CURRENT DESIGN

At the time of paper submittal, the MAV hybrid design, shown in Figure 1, consists of a single MON-25 tank and center perforated hybrid fuel grain (wax-based). The system is pressure fed, with the pressurant also being used as a cold gas for the RCS system. Details of the components are schematically shown in Figure 2. The selected oxidizer-to-fuel ratio of the system coupled with the regression rate of the fuel, leads to a length to diameter ratio 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 motor. This unusual configuration is driven by the geometric constraints of the Sample Retrieval Lander (SRL), which houses the MAV. A volume of ~2.8 m of length by 0.57 m in diameter is available to the MAV.



*Figure 1 MAV hybrid design (Aeroshell/outer skin not shown)*

# Hybrid MAV

Ashley Karp, v. 4/19/2019

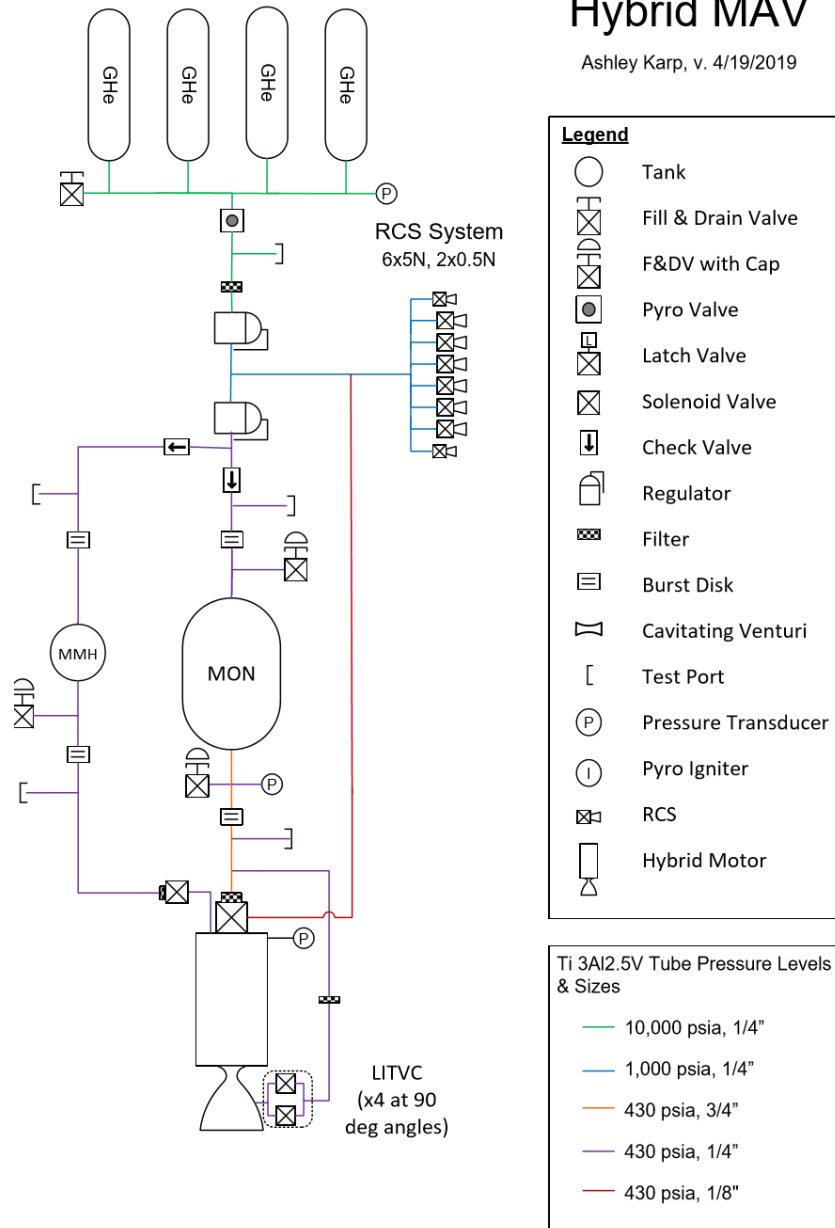
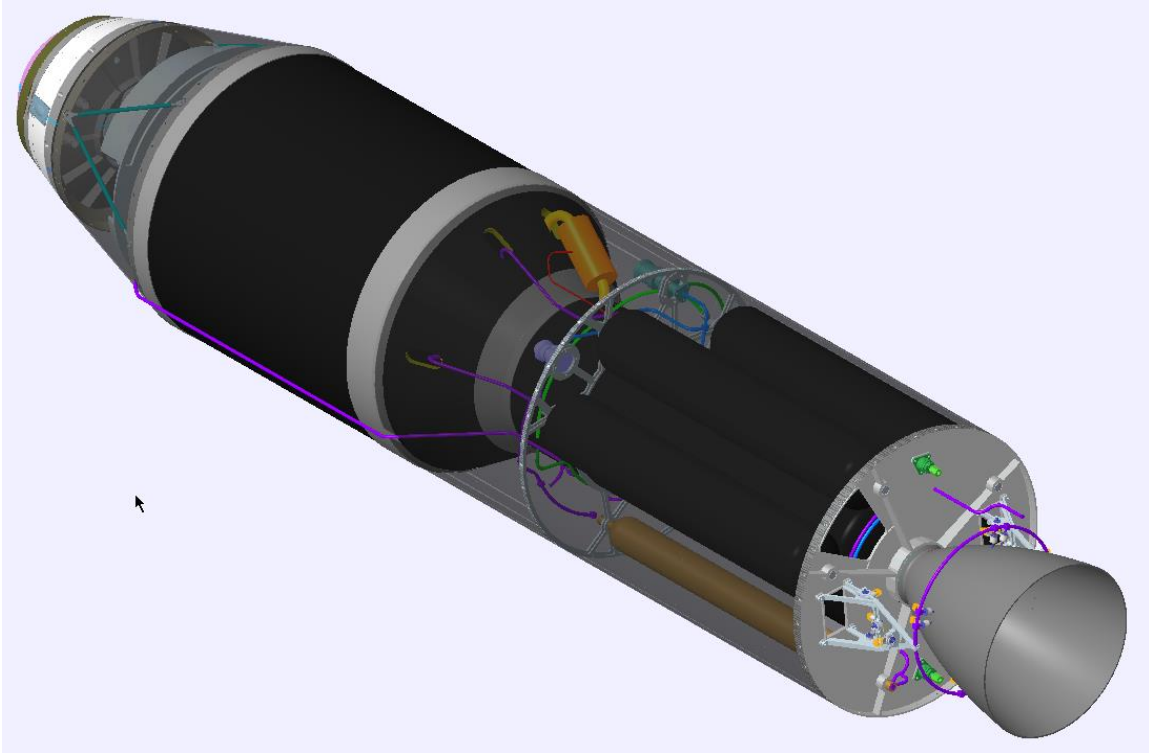


Figure 2 Hybrid rocket system schematic

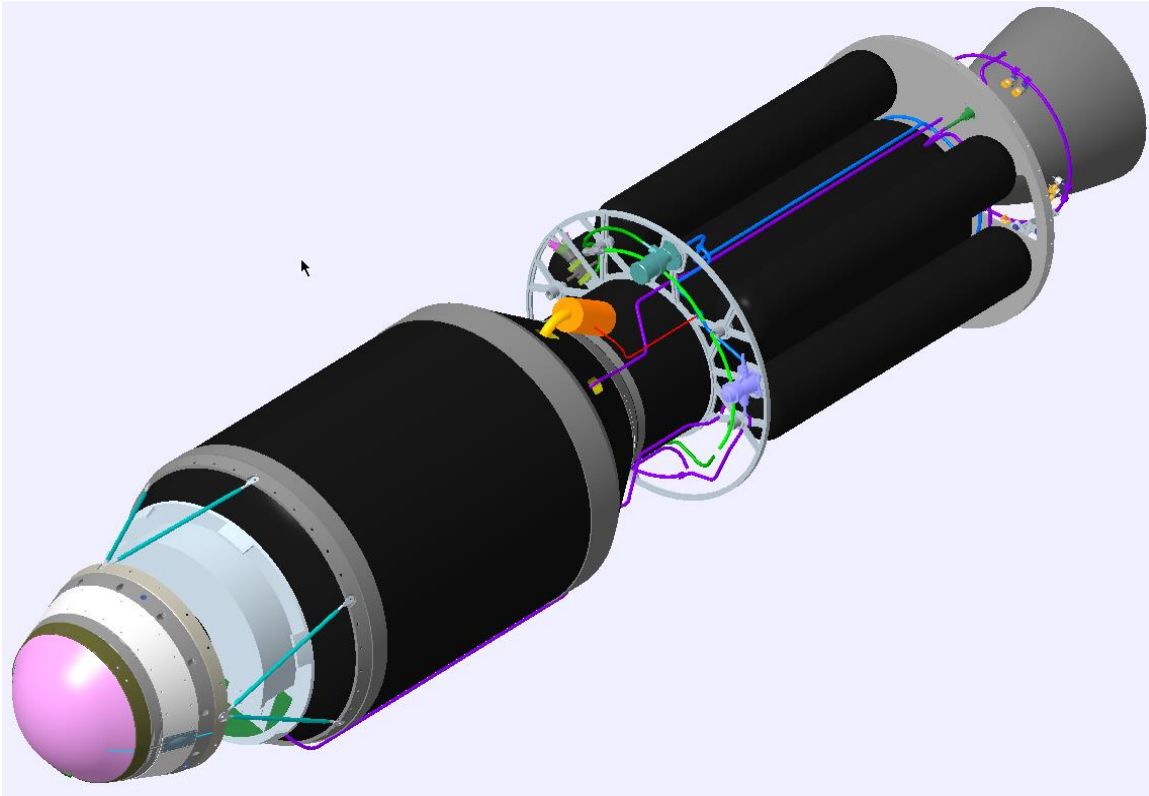
The Reaction Control System (RCS) and Liquid Injection Thrust Vector Control (LITVC) configuration in system can be seen in Figure 3. They are mounted to the aft plate and nozzle respectively. The RCS system uses the helium pressurant as the cold gas propellant. The LITVC employs the MON-25 oxidizer. There are four pairs of valves surrounding the nozzle at 90 degree

intervals. A single valve is intended to offer a degree of thrust vector, and two valves double the deflection.



*Figure 3 MAV hybrid design (Aeroshell not shown)*

Most of the feed system, including many of the valves and regulators, are mounted to the forward mounting plate. This plate also holds one end of the helium and hypergolic tanks in place (see Figure 4).



*Figure 4: MAV hybrid design (Aeroshell not shown)*

## PRESSURIZATION SYSTEM

The pressurization system pressurant is stored in four 10,000 psi helium tanks. The high pressure is required for low temperature operation and compact packaging. The current temperature goal is operation at -20C. This temperature drives the sizing of the high pressure tanks, however there is currently substantial margin in the pressurization system. Recent analysis has shown that the pressurization is capable 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 being heated by the lander 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 this application. The high-pressure pressurant regulator will require further development due to the pressure range and the low temperature range. One risk of the low temperature operation is the seating materials of the dome 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 reaches just below -60C which is out of range of the regulator seat material capability. Similarly, the low pressure regulator components will require development to deal with 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 the specifications of the dome regulator and reduce concerns with low temperature seat material development. Several options will be explored as the propulsion system matures.

The pyro valve isolates the helium tanks from the MON-25 from the point in time at which the tanks are loaded until just before launch. 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, holding the oxidizer as well as being a structural member of the launch vehicle. Current iterations on the design have led to titanium liner with a carbon fiber and epoxy composite overwrap to provide the needed structural rigidity. The tanks 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 6 Degree of Freedom trajectory analysis of the flight to determine the amount slosh dampening required. The best way to attach the baffles to the tank is still being determined, as the ring type baffles may cause structural concerns if directly attached to the liner of the composite overwrap pressure vessel. When tied to the titanium liner, the baffles stiffen the tank at the attach points and the rest of the barrel will bow out under pressure and could potentially result in areas where the composite overwrap is no longer in contact with the titanium liner.

The main oxidizer valve is another component requiring development. Valves like the one required here have not been built since the Space Shuttle program, so some modifications to current designs may be required. The valve opening time will drive the complexity of the design in order to meet the propulsion ignition interval goal.

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

## IGNITION SYSTEM

The ignition system design continues to evolve. Hybrid motor tests at SPG and WASP have included pyro matches, gaseous oxygen (GOx) addition, hybrid heater motors and triethylaluminum /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 references 5 and 6). This has been accomplished with leaving ignition fluid, or another heat source, on throughout motor operation. TEA/TEB is pyrophoric with oxygen, and slightly reactive with  $N_2O_4$ , though testing at Whittinghill in a vacuum environment has not shown it to be reactive enough to initiate combustion without the oxygen lead. While it is not impossible to add a small GOx source to the flight design, it would increase the complexity of MAV hybrid concept. Additionally, the low density of the GOx gas is not desirable. 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 MMH as an ignition fluid. It has been demonstrated in bipropellant thrusters as being hypergolic with MON-25 at temperatures down to -40C (see reference 7) under vacuum conditions. Whittinghill has just 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.

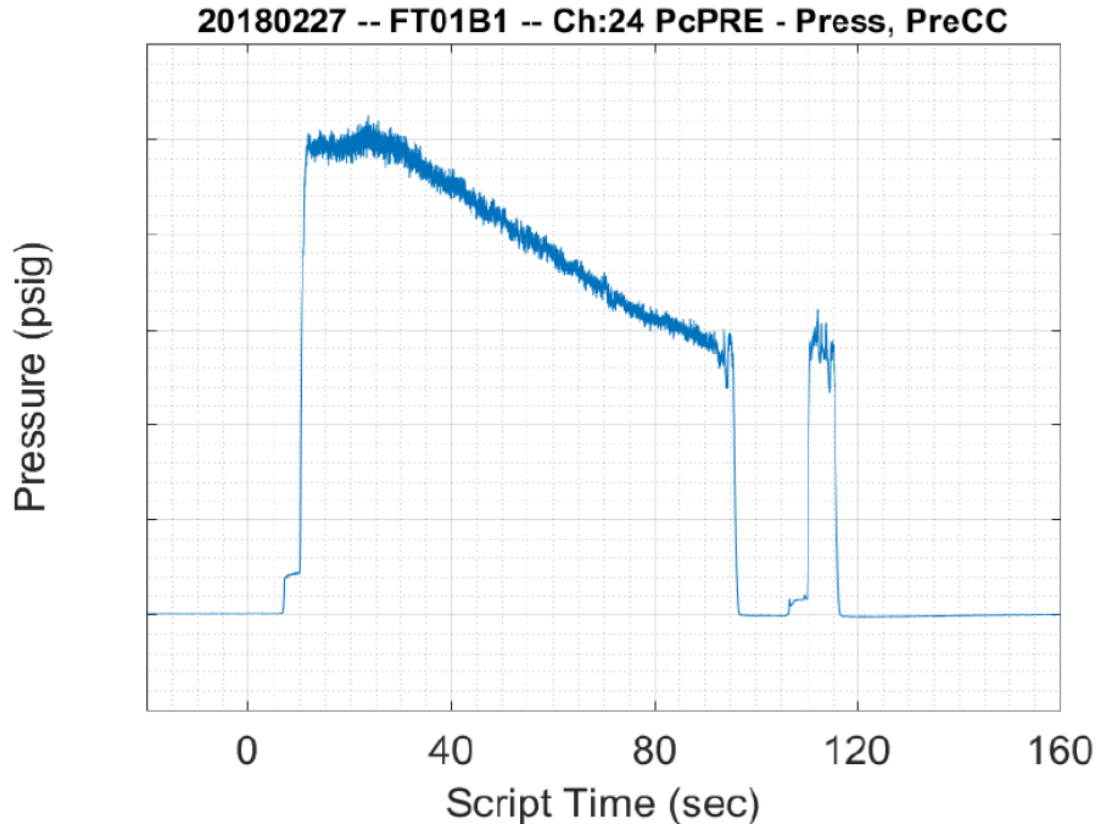
As a longer term goal, Purdue University is continuing their development of solid hypergolic additives for the fuel (see references 8, 9, and 10). Operationally, these would lower the complexity of the vehicle by achieving ignition by simply opening the oxidizer valve. This would eliminate a number of components and make the system safer during Earth handling. Purdue has been making progress investigating solid hypergolic additives in SP7 and has successfully hot fired a horizontal, subscale motor with both MON-3 and MON-25. Future tests at Purdue University include incorporating the additives and testing hypergolic ignition in a slightly larger motor inside a vacuum chamber.

There are several challenges with using hypergolics. The first is the pressure effect: reaction time is inversely proportional to pressure. In theory, as pressure goes to zero, the reaction time increases, potentially becoming too long to get ignition in the motor. MMH/MON thrusters have been demonstrated at low pressure in the past. A Computational Fluid Dynamics analysis has been completed to evaluate the pressure and contact time for liquid hypergolic options in both impinging doublets and triplets with MON-25. Other devices have been investigated to increase the pressure and ignition time (reference 11). The most promising solid additives have only been drop tested in low pressure conditions so far, so the effect of pressure in a motor configuration is yet to be demonstrated. However, additional testing is planned for later this year.

The second potential issue is the handling of these materials. Most liquid hypergols are hazardous or toxic. The solid hypergols are reactive with water, which would preclude hydrostatic proof testing of the motor. Some sort of proof test will be required, so alternative methods will be investigated if this option is chosen. Therefore, while there are many benefits to using a hypergolic fluid or a solid hypergolic additive, the system implications must be investigated further.

## HYBRID MOTOR

The best demonstration of mission performance of hybrid rocket motor thus far, was Whittinghill's FT-01 (reference 5). It included a near full duration burn with an autonomous restart. This test was done with MON-3 and SP7. As can be seen from Figure 5, the test had stable combustion and a pressure drop during the burn. The pressure drop was caused by excessive nozzle erosion. One potential fix to throat erosion was investigated in FT-02 in a change in nozzle materials, however, the design change did not improve the erosion rate. There is discussion of the flight design using fuel film cooling to protect the throat from excessive erosion. This is proposed to be accomplished by adding HTPB in the aft end mixing chamber so it forms a fuel rich layer over the throat material. Recent tests of this concept were not particularly promising.



*Figure 5 WASP's FT-01 with MON-3 and SP7(reference 5)*

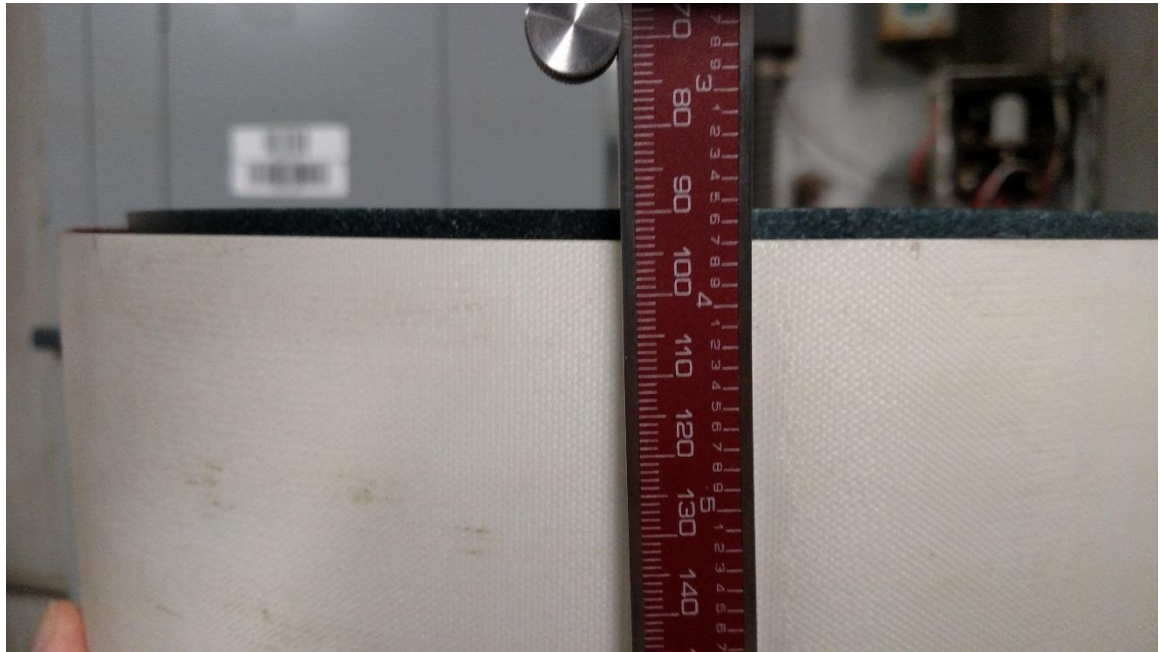
There are 6 flight-sized development motor tests planned for 2019 to increase the technology readiness level of the hybrid rocket single stage to orbit concept. These tests are planned to address the major identified risks and concerns with the hybrid motor. Whittinghill's tests (A-D) have certain objectives and SPG's test (E-F) have different objectives.

During the Martian temperature cycles and during Earth processing and launch events, the fuel grain could be exposed to temperatures ranging from -40 to 40C and therefore the propulsion system will be qualified from -50 to 50C. Attempts at bonding to the wax-based SP7 have indicated some desirable tensile properties near room temperature, but if the sample ends are bonded to fixed surfaces and the sample cooled, the adhesives fail.

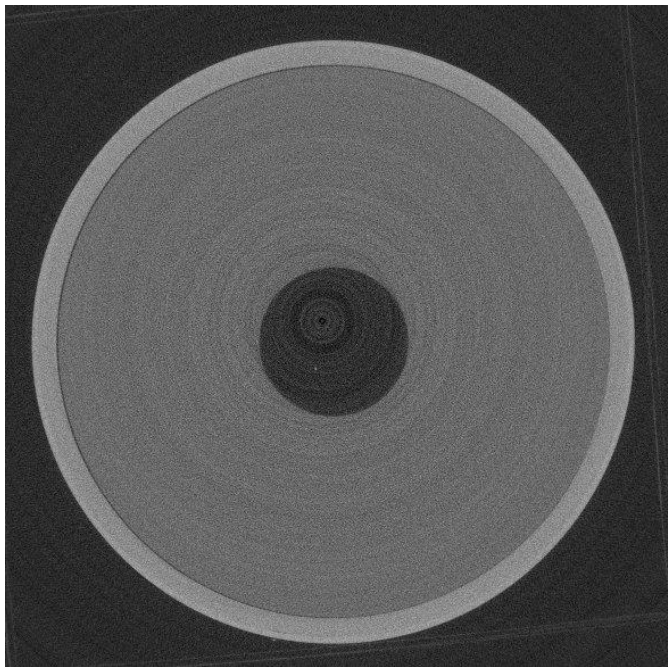
Motor A was the first test to be subjected to -20C ignition and there was a concern that the fuel grain would debond from the fuel grain cartridge and crack during pressurization and possibly eject materials. A new assembly technique was developed to keep the grain in compression over that temperature range. The fuel grain for motor A was assembled in a freezer, in this case at -20C. The grain was placed in an insulated box and rolled into the freezer. SP7 handles temperature ranges well, but it doesn't respond well to temperature shocks. Previous testing and modeling have indicated that the fuel grains survive in temperature swings of 10.8 C/hr (reference 12). Therefore, this value has been taken as a limit to the temperature ramp rate. After several days of cool down, the ambient temperature cartridge was lined with an uncured RTV and slid over the cold fuel grain, a 25 lbm weight was put on top and the insulated box put back over it while still in the freezer. The assembly was rolled out of the freezer and allowed to return to ambient temperature over several days. Once it was opened, it was found that the fuel grain had expanded during the warming process, before the RTV had cured, and the grain had shifted out of position (see Figure 6). This was likely caused by the expansion of the SP7 during the warming process, further compounded by a wedge shaped silica cloth phenolic insulation piece bonded to the inside of the cartridge. The SP7 contacted the wedge insulator and



lifted the cartridge and weight during the thermal expansion. The fuel grain was then machined to print, such that the aft face was flush with the cartridge. After further analysis and inspection at cold temperature (see Figure 7), it was determined that the fuel grain was not in contact with the wedge insulator and therefore the ground test duration will be shortened to reduce the risk of burn through. Future bonding will incorporate specialized tooling to ensure proper grain location in the cartridge. The cartridge-loaded grain was cooled again to -20C and inserted in the heavyweight motor case in advance of shipping to Mojave for the ground test.

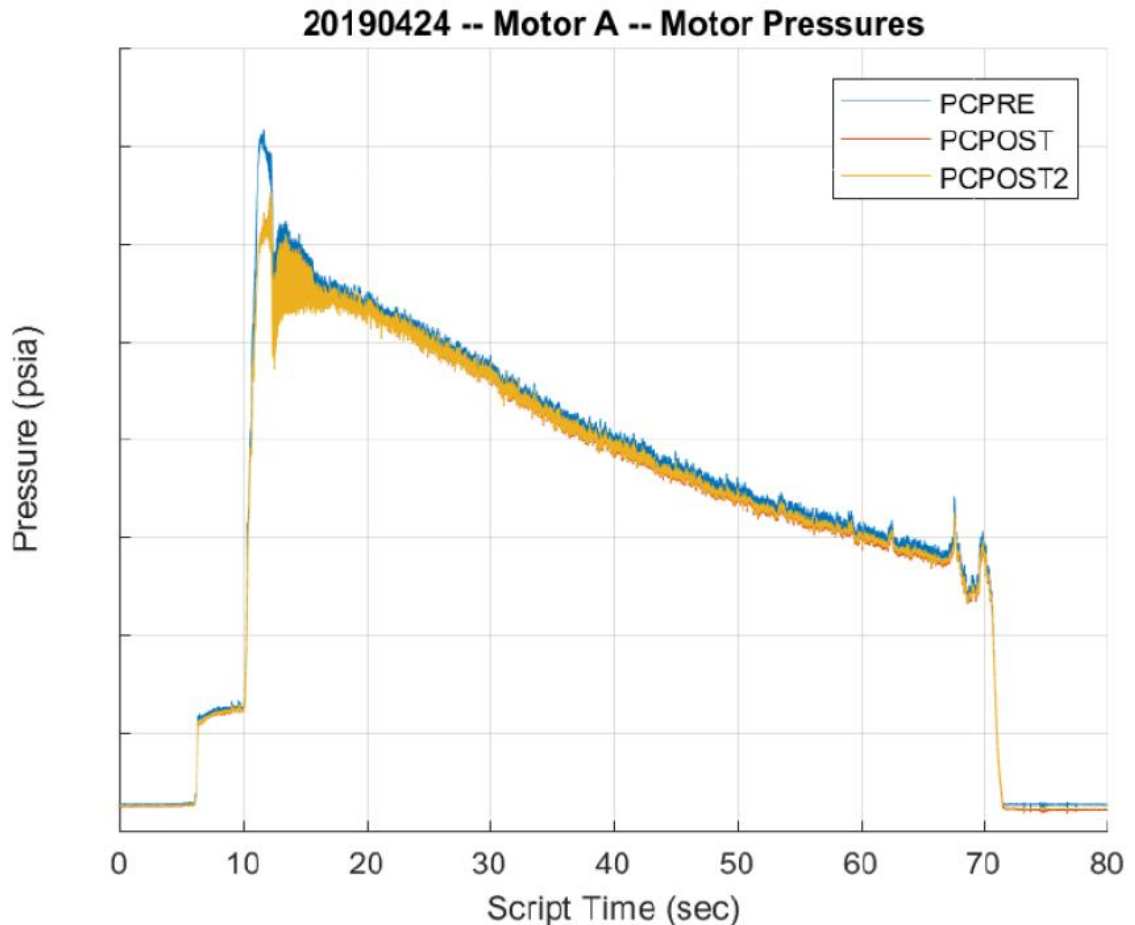


*Figure 6 Motor A grain expansion post cold assembly(fuel should be flush with the cartridge)*



*Figure 7 CT of Motor A Grain at ~-20C showing gap (black line) between SP7 and SCP*

The first motor (Motor A) using MON-25 and SP7 was fired on April 24, 2019. The test duration was set for 60 seconds and the combustion was stable. Initial transients are due to ignition fluids startup issues. The motor exhibited higher than expected SP7 regression in the front end of the motor. HTPB fuel added in the aft end of the motor to provide a fuel rich boundary layer to protect the nozzle throat, but nozzle erosion was still too large. Several issues were seen in post-test disassembly that need to be addressed and at the time of papers submittal, these issues are still being resolved.



*Figure 8 Motor A post combustion chamber pressure*

Analysis of the motor for a flight system, with predictions of a regression rate for SP7 with MON-25 have led to a reformulation of the SP7 to get a mix with 85% of the regression. Reformulation involves an adjustment of the fuel constituents by mass to achieve the target regression rate (no addition of new constituents). This fuel reformulation, called SP7A, was analytically formulated first by SPG and verified by small burn rate motors at different formulations representing different burn rate predictions. A curve fit was used to pick the final formulation. Full scale grains segments are being mixed, poured and cooled for SP7A in a similar manner to what was used for SP7 (reference 13).

Motor B will be static fired at -20C with MON-25 and SP7A. The grain is planned to be assembled in a -40C or lower freezer temperature to ensure that the grain will be in compression over the -50 to 50C qualification range. Motor B will have a slightly larger fuel grain diameter to obtain the total impulse required. Motor B could have MMH as the ignition fluid, however additional ignition tests are not currently planned prior to this motor test.

Motor C and D will be a -20C demonstration of a near flight like design with the objective of achieving high combustion efficiency, low nozzle erosion, high fuel utilization and stable combustion with SP7A and MON-25 and the flight ignition system, likely MMH. Motor C will be fired at WASP's Mojave test facility.

Motor D will have a 40:1 expansion nozzle and will be fired at -20C the NASA WSTF. This test will be in a vacuum and will test the LITVC system performance. The LITVC system, designed for operation in the near vacuum environment of Mars, can't be adequately tested in a facility with an Earth ambient back pressure. Motor D's fuel grain will be assembled into the liner at MSFC and that assembly slid into the motor case at -40C or -50C depending on freezer availability. Further assembly of the motor will occur at WASP's facility. The case with fuel grain will return to MSFC for computed tomography (CT) inspection, thermal cycling over the -50C to 50C range and the CT scanned again to inspect for damage and then shipped to WSTF for testing.

SPG, in addition to doing the grain reformulation, is investigating different flight-weight case options for the Mars flight design. Titanium liners with composite overwrapped grains are being investigated as a means to minimize mass. For this to be a low mass solution there cannot be any flanges in the forward dome to case barrel and case barrel to aft dome interfaces. The exit cone may still be bolted on. Titanium end domes and the center section will need to be loaded with insulators and fuel grains and then welded in place. This assembly will then be over wrapped with composites. Due to the high CTE of the fuel, the composite will need to cure at a low temperature compared to typical composite overwrapped pressure vessel (COPV) tanks. SPG will build and ground test two iterations of the motor design. Other objectives of these tests include evaluating mixing device designs. These motors (E and F) will be fired with MON3 at SPG's Butte, MT facility.

#### LITVC AND WHITE SANDS TEST FACILITY TESTING

LITVC was selected as the baseline thrust vector control for the hybrid propulsion system back in 2015. Advantages included that the liquid injectant, MON-25, was available from a system already on the vehicle and that the initiation of the vectoring, from the valve actuation, injectant flowing to shock formation which causes the vector, is very quick. Additionally, a major benefit is that a LITVC system is less sensitive to low temperature operation than other thrust vector control methods.

LITVC has been used for Titan Boosters (see references 14 and 15), but NASA hasn't done much testing or further development of the concept since it was evaluated for the Space Shuttle Boosters (see references 16 and 17). Therefore, the tools for evaluation need to be redeveloped for use in the MAV design. In order to gain confidence in the design, we need to validate the tools and demonstrate the LITVC technology. WSTF has a vacuum facility for testing moderately sized rocket. Reference 18 discusses the WSTF vacuum system and adjacent Test Stand 401 operation. The WSTF testing is planned for Test Stand 403 (Figure 9), but uses the same vacuum system with a slightly different thrust measurement system as test Stand 401.



*Figure 9 WSTF TS 403 Vacuum Chamber*

Test Motor D will be mounted vertically in the chamber over the diffuser. Thrust will be measured via a three load-cell system. Pre and post calibration of the system, with known side loads on the motor case, will be required to ensure accurate evaluation of the measurement of the relatively small side loads delivered by the LITVC pulses. The MON-25 run tank will be mounted inside the vacuum chamber on the platform that suspends the motor and contains the thrust measurement system. WSTF personnel are doing preliminary designs on the needed systems to ensure that the oxidizer flow rates are met. Considerable design work will be put into getting the MON-25 and hybrid motor down to -20C at the test time. This includes installing a run tank with a built in LN<sub>2</sub> heat exchanger and a shroud around the motor to chill the motor. The shroud may hinder the viewing of the plume, which should rotate during LITVC operation. Cameras will be set up inside the vacuum chamber to attempt to measure the plume deflection.

### MON-25 CHARACTERIZATION

WSTF and Purdue University are characterizing the MON-25 for physical, thermodynamic and system properties. While there is some MON-25 data available, Reference 19 states 'the expressions are based on available data; Rocketdyne reports that additional characterization (or confirmation) of the N<sub>2</sub>O<sub>4</sub>-NO system is recommended'. As such, the MON-25 characterization information would be helpful across several programs and funding is being augmented from other sources than just the MAV effort. At the time of the paper, Purdue University had started viscosity measurements, but has not yet published the results.

### **SUMMARY AND CONCLUSIONS**

The MAV hybrid has completed a lot of design work and testing in the last several years. There remains a lot of testing to complete this year before the down selection of the MAV propulsion system for further development, qualification and flight. Critical technologies are being investigated and demonstrated in the various assembly and demonstration tests. The testing this

year should help position the hybrid rocket design as a viable option for the MAV in the upcoming down selection which is anticipated this coming fall.

### **FUTURE WORK**

A lot of the effort for this year remains to be completed. Testing pace will pick up. Whittinghill motors B and C will be tested at Whittinghill's test facility. Whittinghill Motor D will be inspected, thermocycled and inspected again at MSFC and tested at WSTF. This will demonstrate motor stability, fuel utilization, fuel integrity, motor performance and LITVC performance.

SPG motor's E and F will be tested at SPG's test facility. These will demonstrate case manufacturing techniques required to support the fuel and minimize the motor weight.

It should be a fast and furious finish to get all of the planned testing completed before the down select between the single stage to orbit hybrid rocket and the two stage to orbit solid rocket concept in late 2019. There will only be one MAV propulsion concept going forward after that down selection.

### **ACKNOWLEDGMENTS**

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