Update on Technology Development Plan for a Low Temperature Hybrid Mars Ascent Vehicle Concept

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Technology development to mature a hybrid rocket option for a potential Mars Ascent Vehicle has been underway at the Jet Propulsion Laboratory and Marshall Space Flight Center. A conceptual design was completed in 2016 and has been used to determine the motor size for risk reduction development. The task plan for the FY17 testing, actually completed in mid FY18, is discussed. The major achievement of this effort was successful full scale hotfire testing with a representative ambient Earth storable propellant combination: SP7/MON3. A near term plan, through July 2019 is briefly discussed.

I. Nomenclature

CTE = Coefficient of Thermal Expansion
EDL = Entry, Descent Landing
FY = Fiscal Year
LITVC = Liquid Injection Thrust Vector Control
MAV = Mars Ascent Vehicle
MON = Mixed Oxides of Nitrogen (N_2O_4 plus a percentage of NO by mass)
MSR = Mars Sample Return
SP7 = Wax based Fuel
SRL = Sample Return Lander
TRL = Technology Readiness Level

II. Introduction

Technology development for a hybrid propulsion system for a potential Mars Ascent Vehicle (MAV) has been ongoing for more than two years. The goal of this activity is to increase the TRL of the hybrid MAV to the point at which it could be infused into a potential future Mars Sample Return (MSR) campaign. The desire for a lean MSR[1] with a MAV launch as early as 2026, makes these developments even more timely. Initially this effort was aimed at an Earth-based technology demonstrator as a stepping stone towards Mars. However, the possibility of a near term mission (as early as 2026), shifted priorities. This will be discussed in the following sections. The technology development program objectives and recent achievements will be presented, along with a high-level overview of the plan forward.

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III. FY17 Plan

The original objective of the FY17 testing was to prepare for an Earth-based technology demonstrator for a potential hybrid Mars Ascent Vehicle.[2] With this goal in mind, testing at two subcontractors was focused on achieving stable and efficient combustion with the Earth-storable propellant combination: wax-based SP7 and MON3. MON3 is 97% N_2O_4 with 3% NO by mass. SP7/MON3 was thought to be representative of the Mars propellant combination, SP7/MON30, while enabling low cost ground testing without the need for thermal conditioning on Earth. However, throughout this process, the desire to complete an Earth-based technology demonstrator waned in favor of preparing for a potential Mars mission. Objectives of the full scale hot fire testing became the following:

- High performance: 95% C* efficiency
- Stability: <5% peak to peak variation in chamber pressure
- At least one full duration burn
- Multiple starts on the same motor, preferably without human intervention
- LITVC – nozzle erosion and video of test (and data if possible)

The subcontractors are Space Propulsion Group of Butte, MT and Whittinghill Aerospace, of Camarillo, CA. In addition to the hotfire testing outlined above, each vendor was asked to design a motor for a MAV based on lessons learned testing SP7/MON3.

Many other tasks supported the hotfire test campaign. The most crucial was the manufacture of fuel grains at Marshall Space Flight Center, which required substantial process development, see Ref. 3. The fuel grains proved to be harder to manufacture than paraffin-based fuel grains, which can be spun cast. The SP7 grains were cast in segments and were post machined on the inner and outer diameter and both faces.

The best mechanism to restart the motor was evaluated. While other methods are currently known, hypergolic ignition is still considered the most elegant solution to the multiple starts required on this Single Stage to Orbit rocket. Previous drop testing at Purdue[4] and Penn State[5] identified several promising solid additives. Two of these additives were tested in a subscale motor configuration this year.

A. MON3 vs MON30

The selection of MON3 as the oxidizer for ground testing was made for several reasons. First of all, it is significantly less expensive to buy MON3 and hotfire testing can be performed at ambient conditions. As mentioned above, this was the propellant combination for the Earth demonstrator, MAVRIC[2]. It is well known that MON30 has a higher vapor pressure than MON3 at ambient conditions. However, when you compare each at the desired operating temperature, they are actually fairly similar. The vapor pressure of MON3 at 20 C is 16.2 psi and that of MON30 at -20 C is 7.5 psi.[6] Therefore, no advantage from vapor pressure differences is expected when moving to MON30 at the desired Mars temperature. There may be a disadvantage to using MON30, in that the higher percentage of NO increases the amount of nitrogen in the oxidizer.

This entire effort of the past year and a half was based on MON3, including flight designs; the desire was to based the designs on as much actual data as possible.

IV. FY17 Major Results

In the past year, successful full-scale tests have been completed with a wax-based fuel, SP7 and Mixed Oxides of Nitrogen (MON) oxidizer. Two vendors were tasked with this objective: Space Propulsion Group of Butte, MT and Whittinghill Aerospace of Camarillo, CA. Even though this progress is called FY17, testing extended from the summer of 2017 and spring of 2018. The scale for the motor was determined from the Point of Departure Review design, presented in Ref. 7. Testing this year was completed with SP7/MON3 as a step towards the desired propellant combination: SP7/MON30. A comparison of these two options was made in the previous paragraph.

In general, it was found that it is very difficult to get stable combustion. The primary obstacle was believed to be MON3 vaporization. Some other causes of combustion instability were identified during post-test analysis and subsequently corrected. Substantial effort was put into solving this problem and both vendors independently identified methods to minimize the instabilities.

The regression rate data from the small-scale SP7/MON testing[8] was found to be slightly low compared to the full-scale testing. This is not unexpected, as the fit to the SP7/N_2O data in Ref. 8 slightly low compared to the SP7/MON3 data points. The paper recommended the use of the SP7/N_2O correlation, since there were many more tests to make up the fit. This approach was taken here until a more accurate correlation is developed for SP7/MON3.

The best path forward for a flight like solution will be investigated in the next round of tests.

A. Space Propulsion Group

SPG completed 15 successful ignitions at their test facility in Butte, MT. Figure 1 is a still image from one of these tests. The test stand was built at an angle for safety. If there was a hangfire after the oxidizer valve opened, the MON would drain out with gravity. The fans are included to prevent MON buildup within the test chamber in the case of a non-ignition. SPG's ignition system required human intervention for multiple tests. However, they completed more than one test on a single motor, with the longest test being about 31 s. LITVC was demonstrated qualitatively with the ground nozzle.

The composite case facilitated rapid motor manufacture. There were still interior insulator and injector parts that had some lead time, but the ability to make a new flight weight case quickly was advantageous. There were/are potential issues using a composite case with SP7, with the cure cycle required for good composite case properties. Wrapping the SP7 at ambient pressure with a composite and then curing at an elevated temperature can allow the SP7 to grow due its large Coefficient of Thermal Expansion (CTE) compared to the composite material. That might force the composite case OD to grow slightly before the composite cures. Once it cures at the higher temperature and is brought down to a lower temperature, there is a potential for the grain to be less supported than it would if the case could be cured at ambient temperature. This was theorized to be a contributing factor to cracking observed in the grain post-test. SPG has discussed ways to solve this problem for future testing.

Figure 1 Full scale MAV test at Space Propulsion Group.

B. Whittinghill Aerospace

Whittinghill Aerospace completed six full scale hotfire tests at their facility in Mojave, CA. Figure 2 is a still image from one of these tests. Two of the tests were 90 seconds in duration, including one that had a 5 s autonomous restart. Two of these tests collected quantitative data on exceptionally light-weight, flight-like LITVC valves. A model was created from this data, which was consistent with Ref. 9.

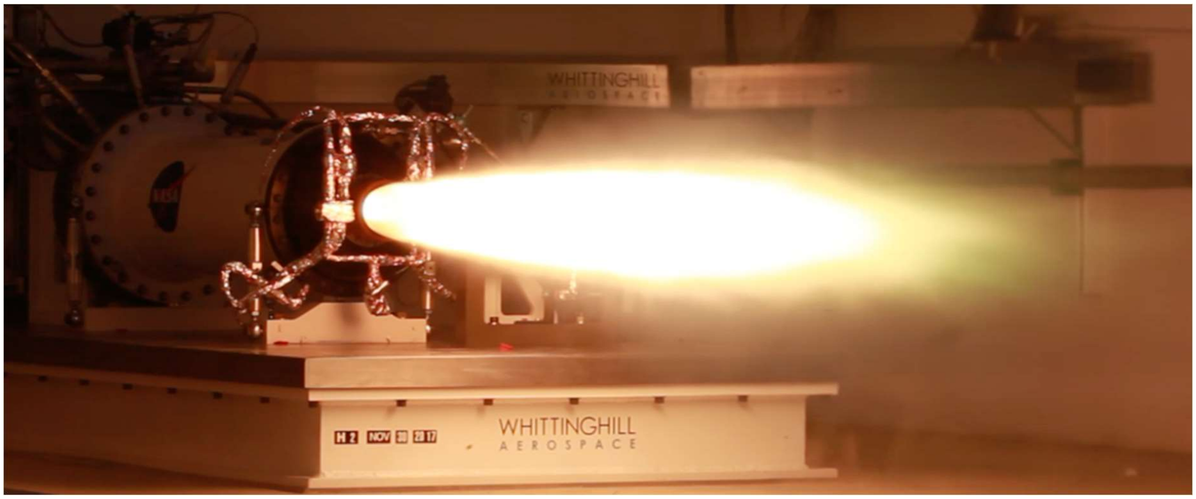

Figure 2   Full scale MAV test at Whittinghill Aerospace.

The horizontal configuration of the Whittinghill test stand (horizontal with access to the plume) made it more conducive to collecting additional data. A team from MSFC measured plume acoustics, case strain gages, temperature and accelerometers. The team brought their own data acquisition system and integrated it with Whittinghill's control system to send the fire signal. MSFC also brought Infrared cameras to record case and plume temperatures. Figure 3 shows a snapshot of the plume measurements from the autonomous restart test. It is not possible to see from the still images, but the black and white version of this data highlights the mach diamonds quite well. Stability can be inferred from a lack of movement of these mach diamonds, which was evident in the video and supported by the chamber pressure data. The camera shut off about 35 s into the burn, but it was restarted for the second ignition. Images from near the end of this period during the first burn are shown in Figure 3. The same time is shown in black and white and color.

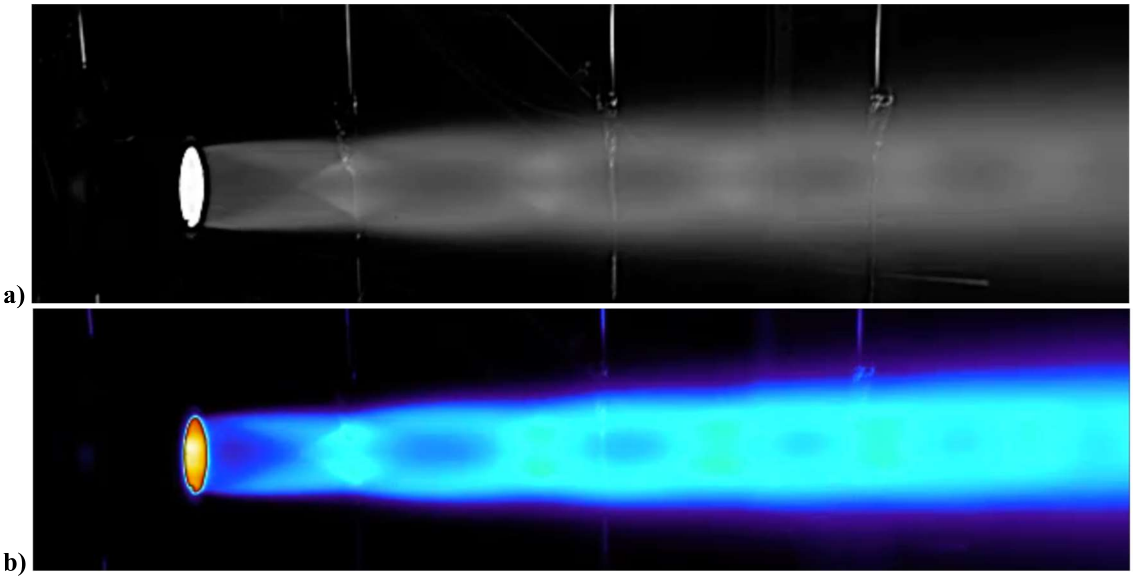

Figure 3: FT-01 test at Whittinghill Aerospace with MSFC's Infrared Camera, both images are at 32.540 s (time selected as a steady state example towards the middle of the test). a) Color represents temperature. b) Same IR data in black and white to highlight the shock structure.

Whittinghill's ignition system was set up for a restart of the motor. A long duration test was run stably and with a short shut down, the motor was restarted. A longer shutdown was deemed risky due to an observed increased regression rate on the top of the motor, potentially a gravity effect. The theory is the SP7 has a melt layer and during operation gravity removes it from the top and it flows to the bottom. After the firing, the SP7 liquid layer can pool in the bottom of the grain. This phenomenon shouldn't be an issue in the actual MAV due to the lower gravity. There has been debate as to what the liquid SP7 will do upon motor shutdown in a vacuum. This will need to be tested in the future.

C. Hypergolic Ignition

Major progress was made in solid hypergolic additives to aide in ignition and combustion stability. Several promising candidates were identified during the past three years of testing. Drop test results at Purdue identified Potassium Bis(trimethylsilyl) Amide (PBTSA) as the best candidate solid additive.[4] Pennsylvania State University completed similar drop testing and identified Sodium Amide (SA) as the best candidate.[5] In these cases, best was identified as the shortest ignition delay. Both additives were successfully tested at Purdue in a small scale (2") motor configuration including multiple relights.[10] Figure 4 shows an image from the first hypergolic ignition using SP7/SA and N_2O_4. More recent work at Purdue has also identified several other promising solutions.

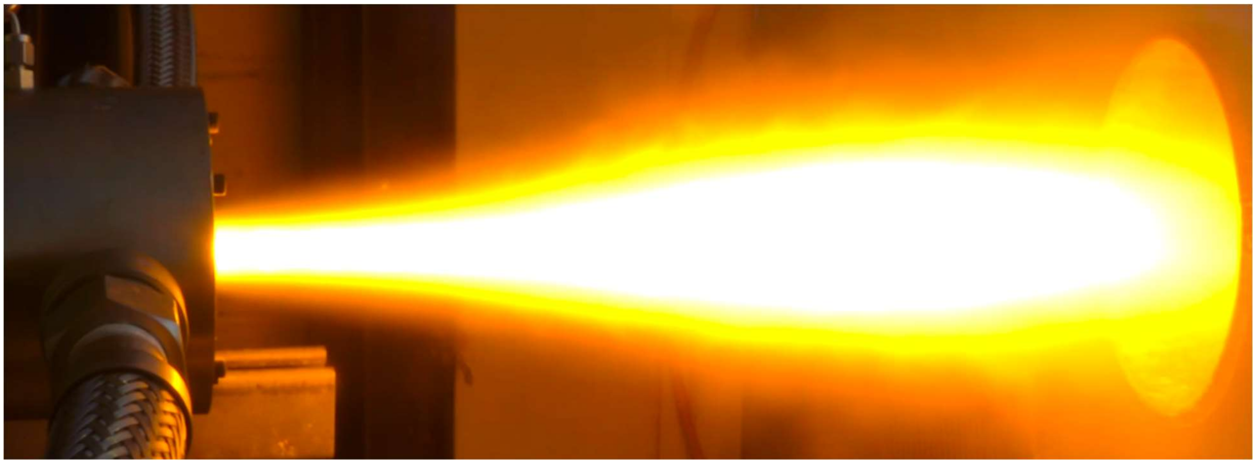

Figure 4: Still image from the first hypergolic ignition at Purdue.

In addition to testing, Purdue has spent considerable effort on how to best incorporate the hypergolic additives in the SP7. Their current solution is grinding the SP7 into small pieces, mixing the additives, and then using a press to make fuel segments. The fuels segments have a lower density than neat SP7 and techniques could be employed to increase the density in the future. Purdue has achieved multiple hypergolic ignitions with SP7 and SA.[10] This demonstrates the potential usefulness of the hypergolic additives in the grains. Now that the ability to hypergolically ignite the motor rapidly and achieve stable combustion has been demonstrated, focus is shifting to identifying the best additive to achieve this while maximizing motor performance.

D. LITVC

Preliminary data from Liquid Injection Thrust Vector Control (LITVC) employed during the hotfire tests has proven the mechanism is feasible for these applications. Visible deflection is evident in the videos and calibrated measurements from the Whittinghill tests are currently being analyzed.

Figure 2 shows mounting blocks on either side of the Whittinghill motor encasing the tiny LITVC valves. The light weight valves were commercially available, but not designed for long term exposure to MON. Flight operations would require a different seat material. The plume was deflected in both directions. The white beam partially hidden by the plume shows a support structure for a load system used to calibrate the side load thrust system by putting a known load on the nozzle before every pulse. There were load cells on both the forward and aft end of the motor measuring side loads during the tests. There was also an overhead camera to visually record the plume deflection and it can be seen from the downstream video as well.

The SPG test shown in Figure 1 did not have the LITVC system installed. It was installed for the last test. They were not tasked with collecting quantitative data, just a video of the plume deflection on at least one test.

V. Major Risks

With the possibility of MSR’26, development has shifted from an Earth demo (Ref. 2) to development for the potential Mars application. The MAV needs to fit within a mass of 400 kg and length of 3 m. Major risk areas have been identified for mitigation over the next year (through July 2019). At that point, the goal is for the technology to be well enough understood to select it (or not) for a development and qualification timeline leading to a potential 2026 launch.

The design presented here is not only a new motor, but a new propellant combination. Motor risks have been consolidated into the following categories. 1) Testing over the past year has highlighted the propellant combination as a possible risk. The MON3 was harder to vaporize than anticipated and early testing suffered from instabilities. Methods to resolve this issue as the oxidizer is changed from MON3 to MON30. 2) LITVC has been demonstrated with MON3 and an Earth ambient nozzle (about 4:1). This may not be representative of MON30 with a vacuum nozzle. 3) The MAV has to be landed into and launched from another planetary gravity well. Therefore, the motor needs to be an aggressive, low mass design. This is what the Point of Departure Review design represented. However, there is a risk that additional mass may be necessary to achieve all the performance goals with the real propellant combination. 4) The Mars environments are very challenging. Tests of slices of the fuel grain suggest it will survive the thermal cycling, but that there are limits to the rate at which the temperature can be changed.[11] While, these ranges are outside what is anticipated for the journey to and launch from Mars, through the ground testing, it was discovered that these temperature changes are possible to achieve on Earth.[12] 5) Finally, there are other materials in addition to the fuel and casing, all of which will need to be investigated.

The requirements on the system have not yet been defined. Since the payload directly affects the size of the MAV, changes in the payload (Orbiting Sample or OS), other subsystems (e.g. structures or avionics) or reliability (e.g. single string vs redundancy) could change the requirements on the propulsion system. The most stressing environments other than the Mars surface will likely be Earth launch and Mars entry. The launch vehicle is still unknown, as is the descent system. Another important, but unknown aspect of the design is the lander. At this point, a lander as opposed to a rover is favored, but it does not have significant reaction mass to assist with the MAV launch. Recontact is a significant concern. At the time of the PoDR, it was assumed that the lander (a rover then) would take the major bending loads from the rocket and the heaters were not to be on the MAV. Both of these assumptions are being reconsidered.

VI. Preliminary Plan through July 2019

With all these risks, a substantial amount of work must be completed in the next year to prepare for a potential selection of a baseline propulsion system. Since the final configuration of an actual Mars mission is still unknown and will be for some time, focus must be placed on the development areas that will make the largest impact without needing to know the exact design. The motor development and understanding propellant combination will be at the top of the list. Most importantly, this means a shift from MON3 to MON30 oxidizer. The MAV has been through two peer reviews over the last several years, and the board has consistently asked for testing to be completed with MON30 if that is to be the design choice.

Several structural issues, such as the CTE mismatch of the fuel and other motor components, must be resolved. This will include material characterization, an investigation of the best way to bond the propellant, and thermal cycling of the motor materials. Additionally, the best way to minimize residual stress resulting from the SP7 grain casting process must be determined.

Finally, system level trades should be completed where possible. Particularly, system level choices that will substantially affect the MAV must be identified. A flight test of the Peregrine hybrid rocket[13] is expected to demonstrate the ability of the avionics being considered for MAV to handle the launch environment. Additionally, data will be collected on the environments induced by this larger hybrid motor to help bound MAV environments. Vehicle level trades will be ongoing at JPL and MSFC and system level (Mars Sample Return Lander, aka SRL) will continue at JPL.

VII. Conclusion

Full scale MAV hybrid rocket tests have been completed at two vendors: Space Propulsion Group and Whittinghill Aerospace. Stable combustion at was achieved but proved to be more difficult than with the small-scale tests reported in Ref. 8. This will likely translate into increased inert mass for a future flight design. Preliminary data from Liquid Injection Thrust Vector Control (LITVC) employed during the hotfire tests has proven the mechanism is feasible for these applications. Visible deflection is evident in the videos and calibrated measurements are currently being analyzed.

Comparing the tests as a whole to the test objectives, the tests have been successful, with up to 90 s of burn time. The regression rate was found to be slightly higher than reported on the subscale data. A full burn duration for the MAV mission will likely involve increasing the diameter of the motor. The motor data approached the C* efficiency requirements. Methods to meet the stability requirements were developed by both vendors and they were demonstrated on several of the tests. One motor was restarted after a long duration test without human intervention. LITVC was operated on multiple tests, including the 90 s test, and quantitative data was taken and is being evaluated. Tests to date have not shown abnormal erosion around the injection ports. While there is a lot of work still to be done, this propellant combination still appears to be feasible for a potential MAV mission.

Acknowledgments

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